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PATENT SPECIFICATION

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COMPLETE SPECIFICATION

Gyroscopes, Gyroscope Stabilised Systems and Gas Bearings for the same

We, STANDARD TELEPHONES AND CABLES LIMITED, a British Company, of Connaught House, 63, Aldwych, London, W.C.2, England, (Assignees of PAUL RIEMANN ADAMS, GERALD BRUCE SPEEN and CARLOS C. MILLER, JR.), do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to highly accurate, low drift gyroscopes, and, in particular, to what may be called the "boot-strap" type of gyroscope, (any type whose drift decreases nearly to zero if the main frame thereof is maintained in nearly perfect alignment with the rotor axis). This invention also relates to a boot-strap system incorporating such a gyroscope and arranged to continually maintain such nearly perfect alignment. This invention also relates to a novel form of spherical gas bearing useful in such a gyroscope.

All the embodiments of the present invention to be described have a "rotor swiveling arrangement" which makes use of gas bearings in order to take advantage of the very low static friction characteristic of such gas bearings, and which at the same time avoids the errors ordinarily resulting from the "bias torque" or unbalanced steady state torque which generally characterizes such bearings. (By "rotor swiveling arrangement" is meant means which supports the rotor while still permitting at least two degrees of freedom of tilt of the rotor axis.

It has become generally recognized in recent years that air bearings (or gas bearings using hydrogen, nitrogen, helium, or other gases) exhibit an essentially zero value of stiction (i.e., static friction), and a very low coefficient of viscous friction. Many suggestions for employing gas bearings either in the spin bearings or in the gimbal bearings of gyroscopes have therefore been made. For producing extremely high performance in extremely low drift gyroscopes, however, these attempts to employ gas bearings have heretofore proved unsuccessful for two reasons. In the first place, the gas bearing, although exhibiting zero stiction and low coefficient of viscous friction, has the fault of producing a small, but continuous, torque or bias force in one direction. For use in a gyroscope gimbal bearing, this type of continuous force is even worse than large viscous frictional coefficients. In the second place, actual measurements on the various types of low drift gyroscopes show that in the truly high grade, low drift gyroscopes now employed in inertial systems, the major errors are not caused by friction in the gimbal bearings but rather by an isoelastic effect and by the thermal effects resulting from the heating of the motor and the spin bearings.

In accordance with the present invention there is provided a gyroscope including a frame, a rotor, means rotatably supporting the rotor relative to the frame, the said supporting means comprising a plurality of pairs of separate gas bearing pads, the pads in each of the pairs being disposed in opposed axial relationship, the rotor having bearing means disposed in coactive association with the gas bearing pads, the axes of the pairs being disposed in coincidence with corresponding centre lines of opposed faces of an imaginary regular polyhedron, and means associated with the frame and the pads to feed gas along the gas bearing pads to form gas bearings for the rotor.

Embodiments of the invention will be described with reference to the accompanying drawings wherein:

Figures 1 and 2 are respective and sectional views respectively of a gas bearing gyroscope using a simple spherical rotor and six gas bearing pads.

Figure 3 is a schematic diagram of a gyroscope stabilized system using a gyroscope

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such as that in Figures 1 and 2, wherein no evacuation of gas is provided.

Figure 4 is a sectional perspective of one simple type of gas bearing pad such as that used in the unit in Figures 2 and 5.

Figures 5 and 6 are perspective and sectional views respectively of a gyroscope having an external rotor supported from the central ball by eight rods and having an intermediate frame member containing six gas bearing pads of the single evacuation ring type.

Figures 7 and 8 are perspective and sectional views respectively of a gyroscope with external rotor supported by six rods and having for its intermediate frame member a gas-tight case within which are eight gas bearing pads of the double evacuation ring type.

Figure 9 is a sectioned perspective of a single evacuation ring type of gas bearing pad such as that used in the unit shown in Figure 6.

Figure 10 is an end view of one type of single evacuation ring type of bearing pad, showing one feasible feed-hole arrangement.

Figure 11 is a schematic diagram of a gyroscope stabilized system wherein the gyroscope uses single evacuation ring type bearing pads such as that shown in Figure 9, and whose intermediate frame member is a gas-tight case which is also evacuated.

Figure 12 is a sectioned perspective of a double evacuation ring type of gas burning pad such as that used in the unit shown in Figure 7.

Figure 13 is an end view of one type of double evacuation ring type of bearing pad showing one possible feed-hole arrangement.

Figure 14 is a schematic diagram of a gyroscope stabilized system wherein the gyroscope uses double evacuation ring type bearing pads such as that shown in Figure 12 whose intermediate frame is a gastight case which is also evacuated.

Figure 15 is a perspective view of one version of the external rotor type gyroscope system that is more convenient for construction, wherein four flat spokes support the rotor from the central ball and wherein eight gas bearing pads are used for support of the central ball.

Figure 16 is a sectional view of the same gyroscope illustrated in Figure 15, but is more complete in that its intermediate frame is shown mounted in ball bearings in a stationary main frame.

Figures 17 and 18 are end views of two bearing pads showing two alternative types of feed hole and gas distribution arrangement.

Referring to Figures 1, 2, and 4, the rotor 1 is a spherical structure wherein two cylindrical cavities 2 are provided, one at each end of the sphere, thus giving it a predetermined preferred axis of rotation about which its moment of inertia is maximum. The rotor 1, which is preferably made of some highly stable material such as quartz or some very high density material and preferably hollow to obtain optimum angular momentum for the mass used, has a very accurately spherical external form and a very high quality exterior finish so that it can act as a bearing surface cooperating with the accurate spherical end surfaces of the gas bearing pads 3. The six gas bearing pads 3, which are of hollow cylindrical form as shown in Figure 4, extend inward as shown in Figures 1 and 2 from the inside of the intermediate frame 4, so that their surfaces match with the surface of the rotor sphere 1. These bearing pads 3 are disposed along three orthogonal axes. Three of them are integral with one half of the intermediate frame 4 and the other three are integral with the other half of this frame. All gas is conducted and distributed throughout this frame to the six pads by a system of manifolding 5. The bearing surfaces are made as large as possible for maximum load carrying ability but some space is left between adjacent pads in order to prevent interaction. Gas, supplied through the manifolding 5 to the reservoirs 6 within the bearing pads 3, is fed through six almost microscopic feed holes 7 to the bearing surfaces where support of the sphere is accomplished.

The surfaces of the circular cavities 2 are used for any convenient type of sensitive pick-off system (not shown), such as capacitive or photo-electric, as well as to predetermine the preferred axis of rotation for the rotor 1.

The intermediate frame 4 is mounted in mechanical bearings 8 as shown schematically in Figure 3 and spun by some external driving mechanism 9 such as an electric motor of gas turbine system. It is obvious that the friction in these bearings 8 will have no effect on the accuracy of the instrument. If the intermediate frame 4 were suddenly spun in this manner, while the rotor 1 was supported on the gas bearings, the rotor 1 would be left far behind and a very long period of time would elapse before the extremely low gas bearing friction could bring rotor 1 up to the speed of the frame 4. In the usual practical case, it is desirable to bring the rotor 1 up to operating speed almost immediately. This may be accomplished through the use of a suitable caging mechanism (not shown) which secures the rotor sphere 1 to the intermediate frame 4 during both the spin-up period and also the slow-down period. When the desired operating speed is reached, the caging mechanism rereleases the rotor 1 which is then supported only on the gas bearings. Once the rotor 1 and intermediate frame 4 are moving together, they will continue to do so as a result of the minute bearing frictions and "windage" effects since the gas within the unit is also rotating with the parts. The pump, or high pressure gas source 10 supplies gas through a

rotating joint or gas slip ring mechanism 11 into the rotating gyroscope assembly. The gas is conducted through the passage 12 into the manifolding system 5 for conduction to the gas bearing pads 3. An exhaust passage 13 is provided for the disposal of access gas or the gas may be returned to the high pressure source for recirculation. This complete assembly is mounted on a platform 14 or within an enclosure and is gimballed through the necessary gimballing system 15, so that the necessary number of degrees of freedom is obtained. Conventional torquers (not shown) are provided at junction between gimbals and between gimbal and platform, as necessary.

The very precise and accurate pick-off arrangement (not shown) which is provided between the rotor 1 and the intermediate frame 4 detects any deviation in position between these two units resulting from some motion of the vehicle carrying the system. The signals thus obtained are carried to a high response servo system, to be described later, which converts these signals into the necessary electrical impulses which are applied to the proper torquers in the gimballing system 15 so as to always maintain the intermediate frame 4 in line with the rotor 1 and keep the pick-off readings at null. These sensitive pick-offs, must precisely determine any deviations in the alignment of the rotor 1 with respect to the intermediate frame 4 about all axes except the axis of rotation, with respect to which relative position, is unimportant.

Although Figures 1 and 2 depict the gyroscope as having six bearing pads 3, which form three mutually perpendicular axes, thus obtaining equal support in all directions, it should be noted that any number of bearing pads 3 may be used as long as three-axis translational restraint is provided.

It should also be noted that the rotational velocities of the rotor and the intermediate frame need not be identical and, as a matter of fact, in some cases it might be useful to have them rotating at different velocities. For instance, in a preferred embodiment of the type shown in Figs. 1 and 2, the rate of rotation of the rotor is within a factor of 10 to 8000 rpm, while that of the intermediate frame is within a factor of 10 of 180 rpm. It is obvious that it is simplest and easiest to have the two rotate at the same velocity, since then the process of bringing the rotor up to speed requires only a simple caging mechanism, whereas if the rotor is to be spun at a higher velocity, some supplementary means of spin-up must be provided in addition to the caging mechanism. The usefulness of an extra high speed rotor is obvious, however, when consideration is given to an application such as a ballistic missile, where the greatest precision is required for only a short period during the initial part of its flight. If the rotor is initially spun up, by some additional technique such as magnetic induction, to a much higher velocity than that of the intermediate frame and allowed to coast, it will very gradually slow down by itself toward the speed of the intermediate frame as the result of the minute frictions existing in the air bearings. This process can take a considerable length of time and during this period much lower drift rates can be expected since drift decreases with increased angular momentum and therefore angular velocity. Finally, when the speed of the rotor equals that of the intermediate frame the two will continue to rotate at the same velocity and the normal drift rate of the gyroscope will be apparent from then on. Thus extra low drift rates can be obtained during the initial period of operation. In a preferred embodiment for this type of application, the intermediate frame is rotated at a rate within a factor of 10 of 8000 r.p.m., and the rotor is set to rotate initially at at least twice this rate.

Referring to Figures 5 and 6, it will be seen that a smaller bearing radius and a larger rotor radius than those of Figures 1 and 2 can be simultaneously achieved by the provision of an external rotor 38 constructed with a comparatively large radius and attached to a much smaller bearing sphere 39 by the use of spokes or supporting rods 40. The six orthogonally arranged bearing pads 27 pass through clearance holes 37 in the external rotor. Therefore, in principle, the operation is the same as in the previous embodiment except for reduced bearing friction accomplished by the use of a much smaller bearing radius.

The design of these bearing pads 27 is an example of a somewhat more complex type of pad using a single evacuation ring 28 as shown in more detail in Figures 9 and 10. In this case, high pressure gas is supplied through manifolding 29 into feed tubes 30 and then to the high pressure chambers 31 from which the gas is brought to the bearing surface through the very minute feed holes 32. Minute grooves 54 may be needed from holes 32 to ring 28 in order to loss down the activity of the self-servoing action just enough to prevent oscillation. As the gas travels across the surface of the pad (and through the lossing grooves if provided) it reaches the evacuation ring 28 from which it is drawn through holes 33 into the vacuum chamber 34 and withdrawn through manifolding 35. A still higher vacuum is also placed on the gas-tight case 36 (which serves as the rotatable intermediate frame of this gyroscope) so as to withdraw any additional gas that has managed to pass the evacuation ring 28. Such an evacuation system can very greatly reduce the aerodynamic damping error. The bearing pads 27 extend from the inner surface of the rotor case 36, through holes 37 provided in the external rotor 38 until they almost meet the

bearing sphere 39. The external rotor 38 is supported from sphere 39 by eight rotor rods 40 oriented like the faces of an octahedron (or like the corners at a cube). Where rods 40 meet the bearing sphere 39 troughs 41 are provided to facilitate construction. Flat areas 42 at the top and bottom of the rotor 38 provide pick-off surfaces.

Figures 7 and 8 show another variation of the external rotor type of gyroscope having eight bearing pads 43 oriented like the faces of an octahedron. As in the previous cases, the bearing shafts 43 extend from the gastight casing 44 (which constitutes the intermediate frame member) through holes 45 provided in the external rotor 46. To the quartz spherical bearing 47 are welded a set of six orthogonally oriented quartz rods 48 which support the quartz external rotor 46; and the usual troughs 49 are provided around weld points. The top and bottom of the external rotor 46 are cut off as shown to provide two flat surfaces 50 for sensitive pick-off purposes. It will be noted in the figures that there are three chambers in each of the bearing pads 43. This represents a still more elaborate type of bearing pad design, shown in more detail in Figures 12 and 13, and incorporating two separate evacuation rings surrounding the bearing surface area. The smallest chamber 51 supplies high pressure gas to the very minute bearing feed holes 89 through the disc shaped chamber 90, whereas the medium sized chamber 52 is used to apply a moderate suction to the inner ring 91 of the pad through the connecting holes 92. The largest chamber 53 then applies a considerably higher suction to the second or outer evacuation ring 93 through the connecting holes 94. In this unit a still higher degree of vacuum is applied to casing 44 in order to evacuate any gas that has been able to escape past both evacuation rings.

Figure 11 schematically illustrates a gyroscope stabilized platform or system using a gyroscope with single evacuation ring bearing pad such as that of Figures 5, 6, 9, and 10. The "intermediate frame" of this gyroscope is in the form of a gastight case 36, and is mounted in mechanical bearings 61 and rotated by a driving system 62. The pump 63 supplies high pressure gas through the rotating joint 64 into a supply channel 65, from which the high pressure air is conducted to the bearing pads through a suitable manifolding sustem in the gastight case 36. The gas from the feed holes 32 (Figure 9) is drawn into the evacuation ring 28 (Figure 9) and withdrawn through the evacuation channel 66 into a gas tight slip-ring assembly 67. The vacuum pump 68 withdraws the air from the slip-ring assembly 67 and may deliver this gas through the tube 69 to the pressure pump 63, if recirculation is desired. The vacuum pump 70 withdraws gas through another slip-ring assembly 71 from the gastight case 36 through the channel 72, located within the rotating assembly. The gas being exhausted by the vacuum pump 70 is conducted to the vacuum pump 68 through the tube 73, where it is combined with the gas from the evacuating ring. The servoing system schematically represented in this figure operates as follows:

The entire system thus far described is mounted on a main frame 74 which is gimballed as before. The gimbals 75 allow rotation of the main frame 74 about two axes. The gear 76 attached to the platform 74 is connected to the motor 77 mounted on the gimbal 75 through a gear train 78. The gimbal 75 is mounted in a gear box 79, which may be rotated by the motor 80, thus providing the two axes of rotation for the main frame 74. The pick-offs (not shown), located between the rotor and the intermediate frame 36 supply electrical impulses indicating their relative positions to the synchronous demodulator and amplifier 81 through electrical slip-rings (not shown) and the inputs 82. A synchronizing unit 83 is provided on a suitable member of the intermediate frame 36 and a wiper arm 84 in contact with the synchronizing unit 83 provides the interrupted signal or pulses to the synchronizer demodulator 81 through the input 85 for reduction of the signals to main frame 74 rather than intermediate frame 36. The output 86 of the amplier 81 is directed to input lead 87 of motor 77 to control the tilt of main frame 74 while the output 88 of the amplifier 81 is used to control the motor 80 for azimuth corrections.

In this way, the alignment is maintained within a very small angle at all times. The more accurate the alignment so maintained, the more significant is the property of zero static friction possessed by gas bearings. Accordingly the servo system for main frame 74 should preferably be of a very refined form capable of maintaining alignment to a very small fraction of a degree (although shown in very crude form for ease of illustration).

It will be noted that by means of synchronizing system 83 the pick-off information obtained between the rotor 38 and intermediate frame 36 is effectively transformed into direct information about the rotor's position with respect to the main frame 74. It must be recognized that a pick-off system could just as effectively be placed between the rotor and the platform directly, and in this way eliminate the necessity for synchronization and synchronous demodulation to obtain rotation position information between the rotor case and platform. This could be accomplished by various means, an example of which might be by making the intermediate frame with a transparent portion and using a photoelectric pick-off device operating directly between the platform and the rotor pick-off surface. Also the torquers for the above system although repre-

sented schematically by gearing connected driving motors 77 and 80, may in actual practice, be any type of torquing mechanism and platform suspension. (The operation of this system is entirely analogous to that shown in Figure 3, and the servoing arrangements of Figure 11 may be considered as being also shown applied to Figure 3).

The basic gyroscope system using the double evacuation ring type of gas bearing pad is shown in Figure 14, schematically. Here the intermediate frame 98 is in the form of a gas-tight case and is supported in some sort of mechanical bearings 99 and rotated by some driving mechanism 100. A high pressure pump 101 forces gas through the conducting pipe 102 and rotating joint 103 into the channel 104 from which the gas is distributed throughout the manifolding system in the rotor case 98 to the various bearing pads. The escaping gas in each bearing pad is drawn into the first or inner ring 91 (Figure 12) of each pad, where it is transferred to the first vacuum channel 105. The vacuum pump 106 removes the gas from the vacuum channel 105 through a gas tight slip-ring assembly 107. The gas removed from the first evacuation ring by this vacuum pump 106 is exhausted through tube 108 into the pressure pump 101, where it is recirculated if desired. The gas escaping past the first evacuation ring is drawn through the second evacuation ring 93 (Figure 12) into the vacuum channel 109 and withdrawn by means of a second vacuum pump 110 through the gas tight slip-ring assembly 111. The gas from the vacuum pump 110 is fed into the vacuum pump 106 through the tube 112, so that this gas may also be recirculated. Since the mass of the gas removed from the second evacuation ring is so many times smaller than that evacuated from the first evacuation ring, because of the difference in pressures, the feeding of this additional gas into the vacuum pump 106 is hardly significant and the operation of the vacuum pump 106 is unaffected. Any gas that might escape from the second evacuating ring enters the gastight case 98 and is removed through a further vacuum process into the vacuum channel 113. The vacuum pump 114 removes this gas as before through a gas tight slip-ring assembly 115, and dispels this gas through tube 116 into the vacuum pump 110. Since the gas has been withdrawn twice in the evacuation rings the pressure of the gas escaping from the second ring is exceedingly low and therefore there is only a very small mass flow. Thus a fairly high vacuum can be maintained in gastight case 98, and therefore, when the gas removed from the case 98 is added to the gas in pump 110, it is hardly significant, because of the much higher masses being carried by this pump. As before, the entire assembly is mounted on (or in) a main frame (or outer casing) 117, and gimballed with the necessary gimbals 118. The pick-offs, torquers, electrical slip-rings, and servo system are not shown, since they are of some conventional type, or are similar to that used in the sample system shown in Figure 11.

In each of the above described embodiments, the pumps have been schematically shown on the platforms on which the gyroscope assembly is mounted. It should be noted that it may be more desirable to have these pumps external to the main assembly, if a more convenient location outside the system is found. In such a case the same system operation is accomplished by carrying the necessary vacuum and pressure lines through the gimbals that support the platform or main frame by means of flexible tubing or through gas tight slip-rings such as those used between the gyroscope rotor case and the pumps in the schematics shown herein. It is also sometimes preferable to use a tank of pressurized gas to replace the pressure pump.

The pick-offs that are provided between the gyroscope rotor and the rotor case must be sensitive in at least two degrees of freedom in every case. However, it is important to note that in the case of the external rotor type constructions shown in Figures 5, 6 or 7, 8, a third pick-off device must be provided for the rotation axis because the bearing shafts extend through the external rotor, and if, for some reason, the rotor were to spin about the axis of rotation slightly ahead or behind the rotor case and bearing pads, a contact might occur. If the possibility of any part touching occurs, the rotor case must be accelerated or slowed down accordingly. Such a pick-off need not be very accurate, since it need only ensure that contact does not take place.

All of the above systems and configurations of gyroscopes have their spokes or support rods, as well as their bearing pads, arranged to correspond to the faces of the regular polyhedrons. Thus they are theoretically isoelastic if we assume perfect rigidity of the intermediate case which supports the pads and of the external rotor member which is supported by the spokes or rods. By slightly altering the orientations of the support rods to compensate for imperfect rigidity of rotor and intermediate frame, their anisoelasticity can be reduced to a value dependent only on manufacturing accuracy. Figures 15 and 16 illustrate an example of a configuration which is not theoretically isoelastic, but which is relatively simple to construct, and rigid enough so that its theoretical anisoelastic motion will be fairly small. The gyroscope illustrated is basically the same type of gyroscope as that shown in Figure 7, in that eight bearing pads 119 and an external rotor construction 120 are used. In this case, however, instead of using six spokes as in the previous case, four flat structural members 121 are used to connect the external rotor 120 to the bearing sphere 122. In

this case the external rotor 120 does not have holes for the bearing pads 119 to pt through. Instead, the rotor is made narrow enough for this to be avoided, and as a result, this embodiment like that of Figures 1 and 2 may be operated with its rotor (120, 121, 122) turning faster than its intermediate frame 123, provided that the bearing pads 119 are small enough to allow passage of the rotor support members 121. Therefore, a pick-off for the axis of rotation is optional and may be omitted in such a case. The bearing pads extend inward from the inner wall of the intermediate frame 123. The bearing sphere 122, to which these flat members 121 are welded, is provided with troughs 124 at the attachment points to facilitate efficient assembly. The high pressure channel 125 and the single evacuation channel 126 shown in this figure indicate that the pads 119 are of the single evacuation ring type. However, any arrangement of bearing pads using any system of evacuation is suitable for this design, depending on the application. The flat area at the top of the external rotor 120 is covered with a conductive coating 127 for pick-off purposes (pick-offs not shown).

Figure 16 shows the gyroscope unit of Figure 15 mounted in ball bearings 128, within a main frame 136. The high pressure feed channel 129 is shown feeding into its manifolding system 130 for distribution of gas to the bearing pads 119. A similar vacuum channel 131 and its manifolding 132 are provided for exhausting the evacuation ring. Provision for evacuating the rotor case 123 may obviously be added. The capacitive type pick-offs 133 are shown schematically supported by the insulating stand-offs 134 in a position opposite the conductive ring 127. If a balanced type of pick-off is preferred, conductive rings and pick-offs could be provided both above and below the rotor. The insulating stand-off 135 supports another pick-off for determination of relative angular position about the axis of rotation.

Figures 17 and 18 illustrate some preferred forms of bearing pads which may be used in many of the previously described embodiments which make use of a spherical central bearing. These pads may also be used as spherical bearings, step bearings or thrust bearings in other applications. Many other practical configurations of feed holes and groove arrangements are known to be useful and efficient and those illustrated are for the purpose of example only.

Referring more particularly to Figure 17, this shows a series of six almost microscopic feed holes 180 just as shown in Figures 11 and 12. In this embodiment, however, these are interconnected by a narrow, shallow, circular or roughly circular equalizing groove 181 having a cross sectional area within the range of about half to twice the cross-sectional area of one feed hole, but preferably equal thereto. This type of equalizing groove is particularly effective in increasing the load bearing capacity of the bearing without appreciably increasing its tendency to oscillate. If oscillation tends to take place, it can be eliminated by the use of minute lossing grooves or scratches extending radially outward from the feed holes (or less desirably from one another part of groove 181) to the edge of the bearing, or by stepping back the surface just outside of this groove 181, so that this surface is a little lower than the bearing surface within the groove. In such a case, the difference must amount to something of the order of a few tens of millionths of an inch for the usual sizes of bearings likely to be used in gyroscopes. The area of such lossing grooves or the depth of such step-back should be only slightly greater than necessary to safety prevent oscillations.

Figure 18 shows an alternative form theoretically slightly less efficient, but practically considerable easier to construct. In this form, the six nearly microscopic feed holes used in other embodiments have been replaced by a single, somewhat larger, feed hole 190, which supplies gas through six distributing grooves 191 to the equalizing groove 192. The total depth and width of each groove 191 should be such as to provide a cross sectional area roughly twice as great as that of equalizing groove 192 (preferably between 1.5 and 4.0 times as great). This groove 192 should have cross sectional area of the order of 1/N times that of the central hole 190 where N is the number of radial distributing grooves (i.e., 6 in the case illustrated). Preferably the cross sectional area of groove 192 is between 1.2/2N and 4/2N times the area of hole 190.

It should be clearly understood that the preferred bearing pad forms shown in Figures 17 and 18 may be substituted for the simpler forms shown in any of the preceding figures which use spherical bearings. In those embodiments which require evacuating rings, the same arrangement of feed holes and distributing grooves shown in Figures 17 and 18 may be used but with the evacuating rings added outside thereof.

It should also be understood that any of the forms of gyroscopes employing central spherical bearings may be used with double, single, or no evacuation grooves, even though only a few of such combinations and permutations have been illustrated.

In general, where the case is evacuated the pressure in the case should be kept below 1/10 atmospheres; where an evacuation ring is used as well as case evacuation, the pressure in the case should be kept below 1/30 atmosphere and preferably below 1/100 atmosphere. With double evacuation rings it should be kept below 1/200 atmosphere, and preferably below 1/1000 atmosphere.

In all cases of multistage vacuum—whether

one evacuating ring and then the case, or one evacuation ring followed by another such ring—the ratio of the pressures should be such that more than 80% by weight of all the gas entering a given ring or case is drawn off by the suction connected thereto and less than 20% leaks past to the next stage. Preferably these percentages should be above 90% and below 10%.

The simple essentially ball-shaped rotor shown in Figures 1 and 2 is preferred in most cases. Preferably such simple ball-shaped rotor should have at least 25% of its equivalent outer surface finished as an accurately spherical surface for cooperation with the gas bearing pads. In certain special applications where the *very lowest drift rate* is so essential as to outweigh all considerations of size, weight, complexity or cost, and when at the same time the requirements for withstanding shock, vibration, and acceleration are not too severe, a more complex rotor with inner and outer portions is preferred. When such more complex rotor is used the ratio of its outer radius to the radius of the bearing sphere should exceed 2:1 (and preferably 3:1) and the ratio of the moments of inertia of the whole rotor to that of the bearing sphere should exceed 20:1 and preferably 100:1.

In all such complex rotors, the size of the pads, the spokes, the moats and imperfect areas around the spokes should be such that at least one tenth, and preferably one-fifth of the area of the spheroid is in the form of an essentially perfect spherical surface which usefully engages the bearing pads. The fraction of the area which actually supports the load may be much smaller since the above percentages include the total area of the pad, including evacuation rings and inter-ring zones, but preferably the area actually used for support should not be less than 1/20 of the total equivalent area of the spheroid. (By total equivalent area of the spheroid is meant the area which it would have if its perfectly spherical surface were extended to make a complete sphere).

Where necessary to increase the useful bearing area of the pads, these pads may be enlarged until they become tangent to each other, and may even be further enlarged so that adjacent pads meet along a substantial portion of their periphery, but it is preferred that in all cases at least one-half of the periphery of each pad be kept separate from all other pads, so that at least half of the periphery is available for discharge of gas to the case or to an evacuation channel. No more than half of the periphery of any pad should form a common boundary with other pads, so as to be exposed to interaction from such other pads. Where an evacuating ring or evacuating channel surrounds the actual working portion of a pad or lies between this active portion of one pad and that of the next pad, this shall not be considered as a common boundary region.

WHAT WE CLAIM IS:—

1. A gyroscope including a frame, a rotor, means rotatably supporting the rotor relative to the frame, the said supporting means comprising a plurality of pairs of separate gas bearing pads, the pads in each of the pairs being disposed in opposed axial relationship, the rotor having bearing means disposed in coactive association with the gas bearing pads, the axes of the pairs being disposed in coincidence with corresponding centre lines of opposed faces of an imaginary regular polyhedron, and means associated with the frame and the pads to feed gas along the gas bearing pads to form gas bearings for the rotor.

1. A gyroscope according to claim 1 having means rotatably supporting the frame in relation to a main frame, the main frame being intended to remain rotationally fixed with respect to a mounting, and means to rotate the rotor and the frame with respect to the main frame to reduce precessional drifts resulting from static friction in the gas bearing.

3. A gyroscope according to claim 1 or claim 2 wherein the said rotor bearing means are convex spherical surfaces of the rotor and wherein the bearing pads have concave spherical surfaces complementary with the convex spherical surfaces to form the said gas bearings.

4. A gyroscope according to claim 3 wherein the rotor has an inner portion with the said convex spherical surfaces and an outer portion having a moment of inertia at least twenty times greater than that of the inner.

5. A gyroscope according to any one preceding claim wherein the frame is a gastight case enclosing the rotor and the said supporting means, including means for withdrawing gas from the case.

6. A gyroscope according to claim 5 wherein the pressure within the case is maintained by the withdrawing means at less than one tenth of an atmosphere.

7. A gyroscope according to claim 5, wherein the pressure within the case is maintained at less than one thirtieth of an atmosphere, including evacuation channels in the gas bearing pads communicating with the respective gas bearings, and means for maintaining in the channels a suction sufficient to draw off at least 80% by weight of gas escaping from the gas bearings before this gas can escape into the interior of the case.

8. A gyroscope according to claim 2 or any one of claims 3—7 as appendant to claim 2 having means to rotate the rotor and the frame at different rotational rates with respect to the main frame.

9. A gyroscope according to claim 8 wherein the said rotational rate of the rotor is within a factor of 10 of 8000 r.p.m. and that of the rotor within a factor of 10 of 180 r.p.m.

10. A gyroscope according to claim 8 where-

in the said rotational rate of the frame is within a factor of 10 of 8000 r.p.m. and that of the rotor is initially higher than that of the frame by a factor of at least two, thereafter decreasing towards the rotational rate of the frame.

11. A gyroscope according to any one preceding claim wherein the rotor has at least 25% of its external surface accurately spherical.

12. A gyroscope according to any one of claims 1 to 10 wherein the rotor has the form of an extremely rigid approximately spherical body with at least 10% of its bearing surface accurately spherical and smoothly finished, and wherein the said rotor supporting means comprises at least six gas bearing pads closely paralleling the said accurately spherical surface, at least 50% of the periphery of the bearing surface of each pad being free of contact with any neighbouring pads and communicating with a region of low gas pressure, and means including a channel of high pneumatic impedance for supplying high pressure gas through each of the pads to the space between the pad and the spherical surface of the rotor.

13. A gyroscope according to any one of claims 1 to 10 wherein the rotor is an essentially ball shaped body with the major part of its external surface accurately spherical, and wherein the gas bearing pads cooperate with the said external surface of the rotor to support it with three degrees of rotational freedom.

14. A gyroscope according to any one of claims 1 to 10 wherein at least a part of the rotor comprises a spheroid having concentric accurately spherical convex bearing surfaces over a substantial proportion of its exterior, and wherein the rotor supporting means includes at least six accurately spherical concave support surfaces arranged to closely cooperate with the said convex bearing surfaces, the gyroscope including feeders for supplying gas separately to each of the concave support surfaces, the feeders having sufficient pneumatic impedance to produce a substantial pressure rise in response to a decrease in spacing between any cooperating convex and concave surfaces, whereby a self-servo action takes place to keep the spheroid approximately centred (with respect to the concave surfaces), each of the concave support surfaces being separated from the others by buffer regions of lower gas pressure along at least the majority of its periphery so that the servo action of one shall have no major effect on the servo action of another.

15. A gyroscope according to claim 14 wherein at least one evacuation ring is provided in each of the convave support surfaces, and at least one further evacuation means is provided beyond the ring or rings surrounding the region of discharge of each of the said feeders, and means to maintain in an evacuation ring sufficient suction to draw off more than 80% by weight of all gas crossing the ring, thus allowing less than 20% to leak past the ring.

16. A gyroscope according to any one preceding claim in which each gas bearing pad support surface has a substantially ring-shaped equalizing groove surrounding a substantial area thereof, and has distributing grooves connecting the equalizing groove with the gas supply.

17. A gyroscope according to claim 16 having lossing grooves extending outward from each equalizing groove towards the periphery of the support surface to reduce any tendency of the bearing to oscillate.

18. A gyroscope according to claim 2, or to any one of claims 3 to 17 as appendant to claim 2, having servo means for tilting the main frame with respect to a vehicle in such a direction as to reduce misalignment between the axes of the motor and the frame.

19. A gyroscope substantially as described with reference to Figs. 1 and 2 of the accompanying drawings.

20. A gyroscope substantially as described with reference to Figs. 5 and 6 of the accompanying drawings.

21. A gyroscope substantially as described with reference to Figs. 7 and 8 of the accompanying drawings.

22. A gyroscope substantially as described with reference to Figs. 15 and 16 of the accompanying drawings.

23. A gyroscope according to any one of claims 19 to 22 including gas bearings substantially as described with reference to Fig. 4 or Figs. 9 and 10 or Figs. 12 and 13 or Fig. 17 or Fig. 18 of the accompanying drawings.

24. A gyroscope stabilized system substantially as described with reference to Fig. 3 or Fig. 11 or Fig. 14 of the accompanying drawings.

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Chartered Patent Agent,
For the Applicants.

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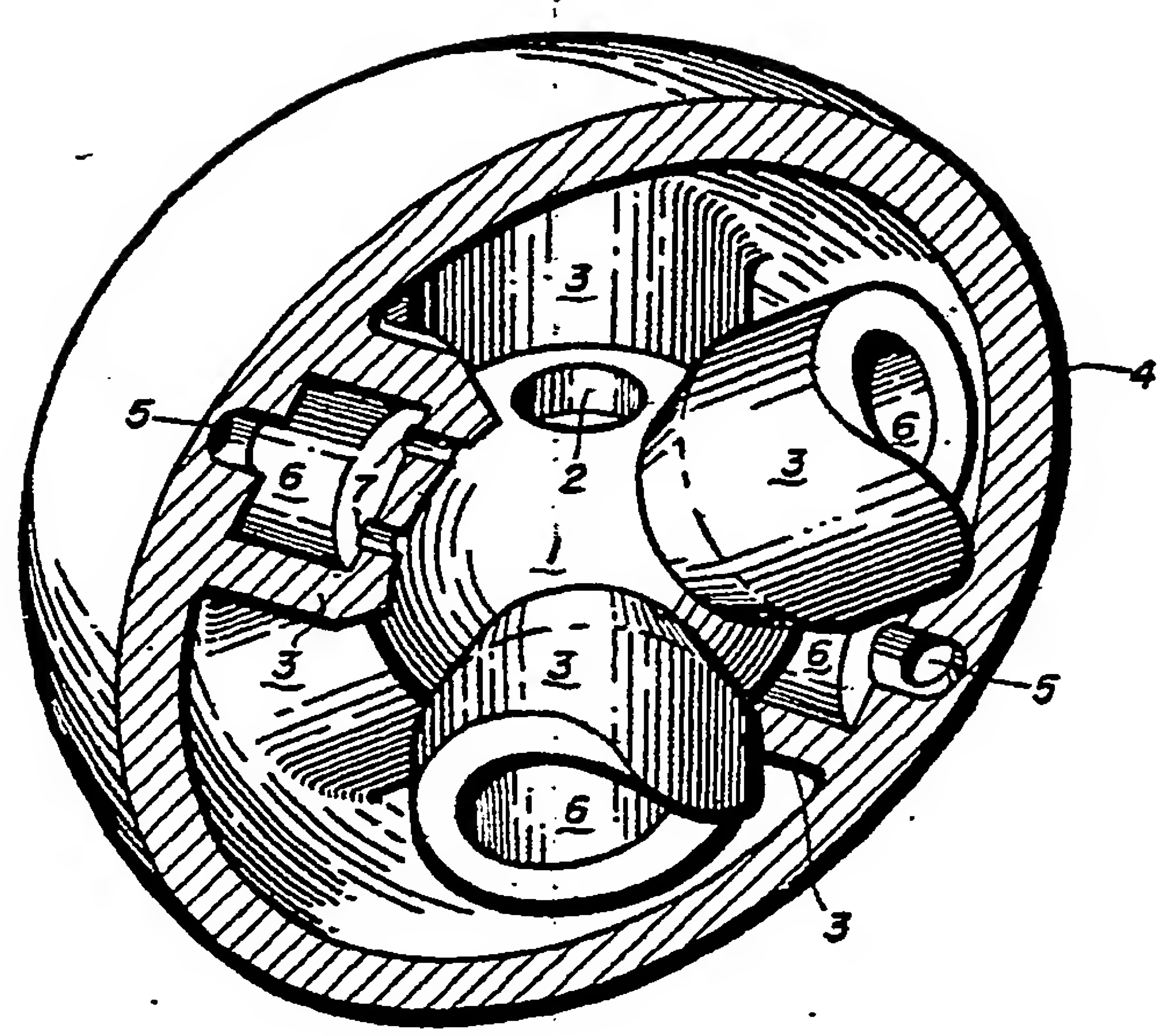

FIG. 1

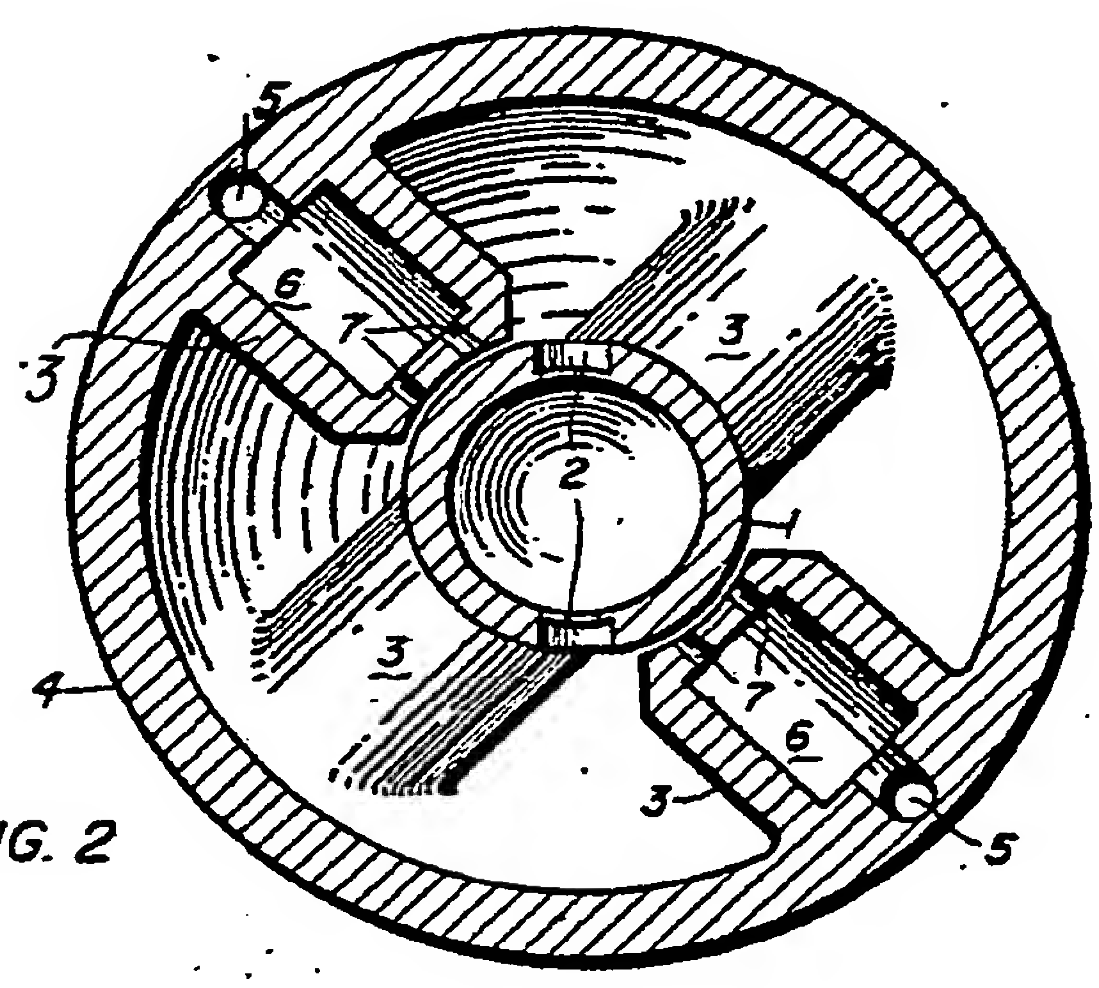

FIG. 2

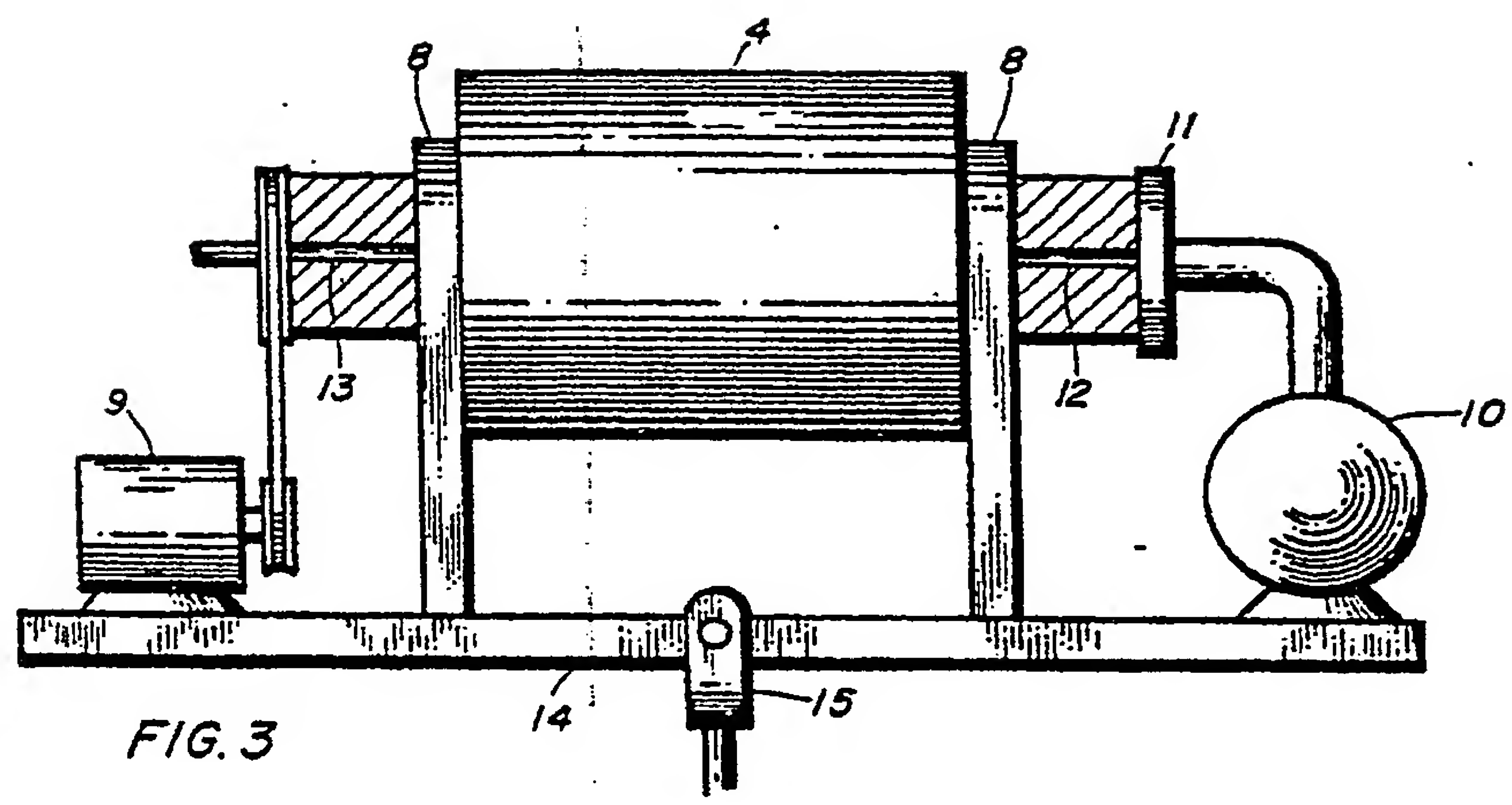

FIG. 3

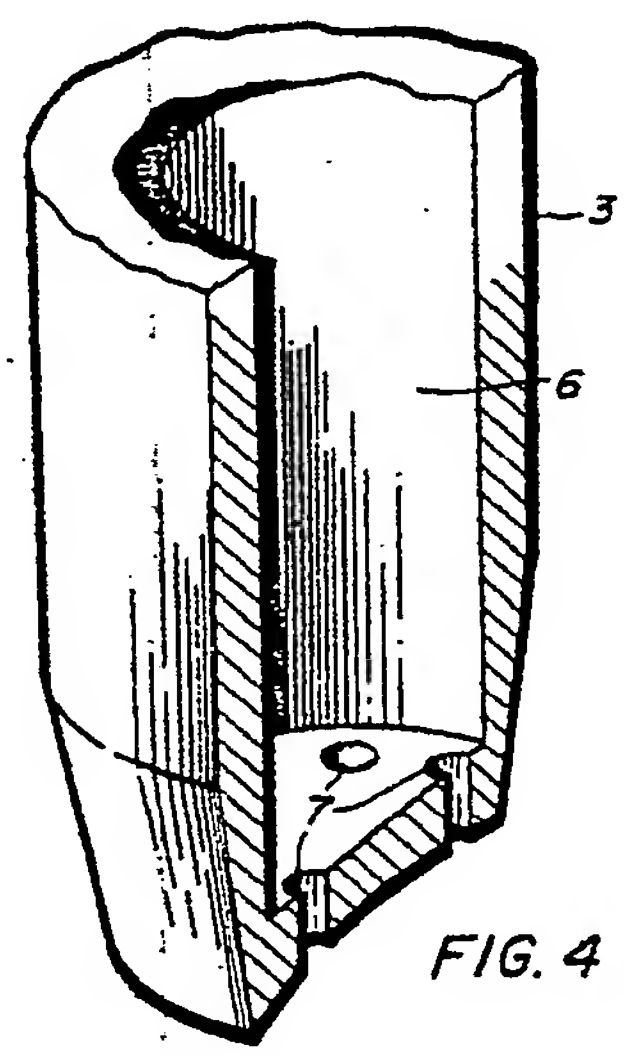

FIG. 4

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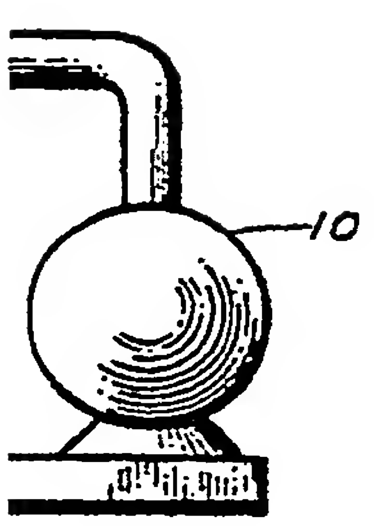

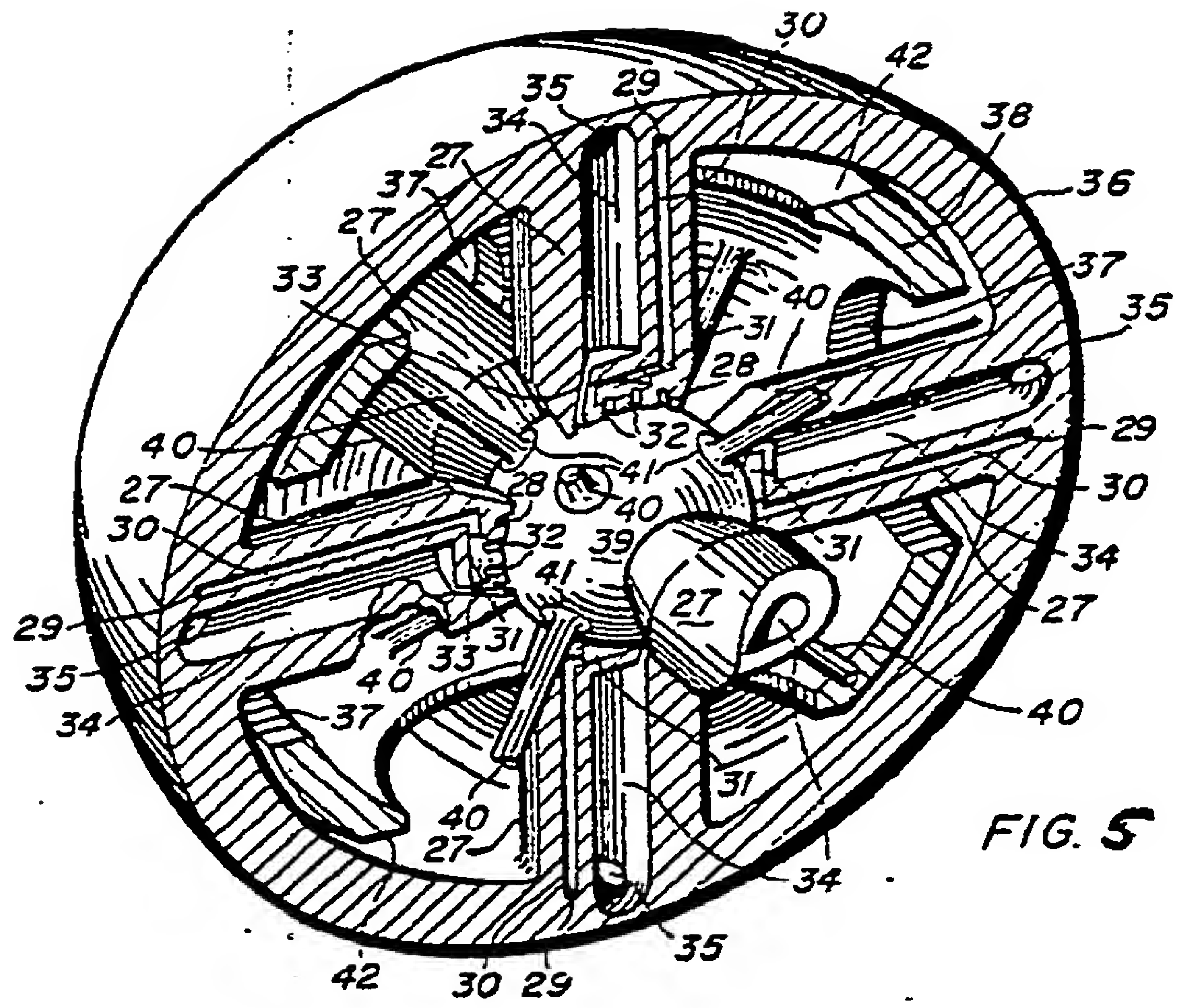

FIG. 5

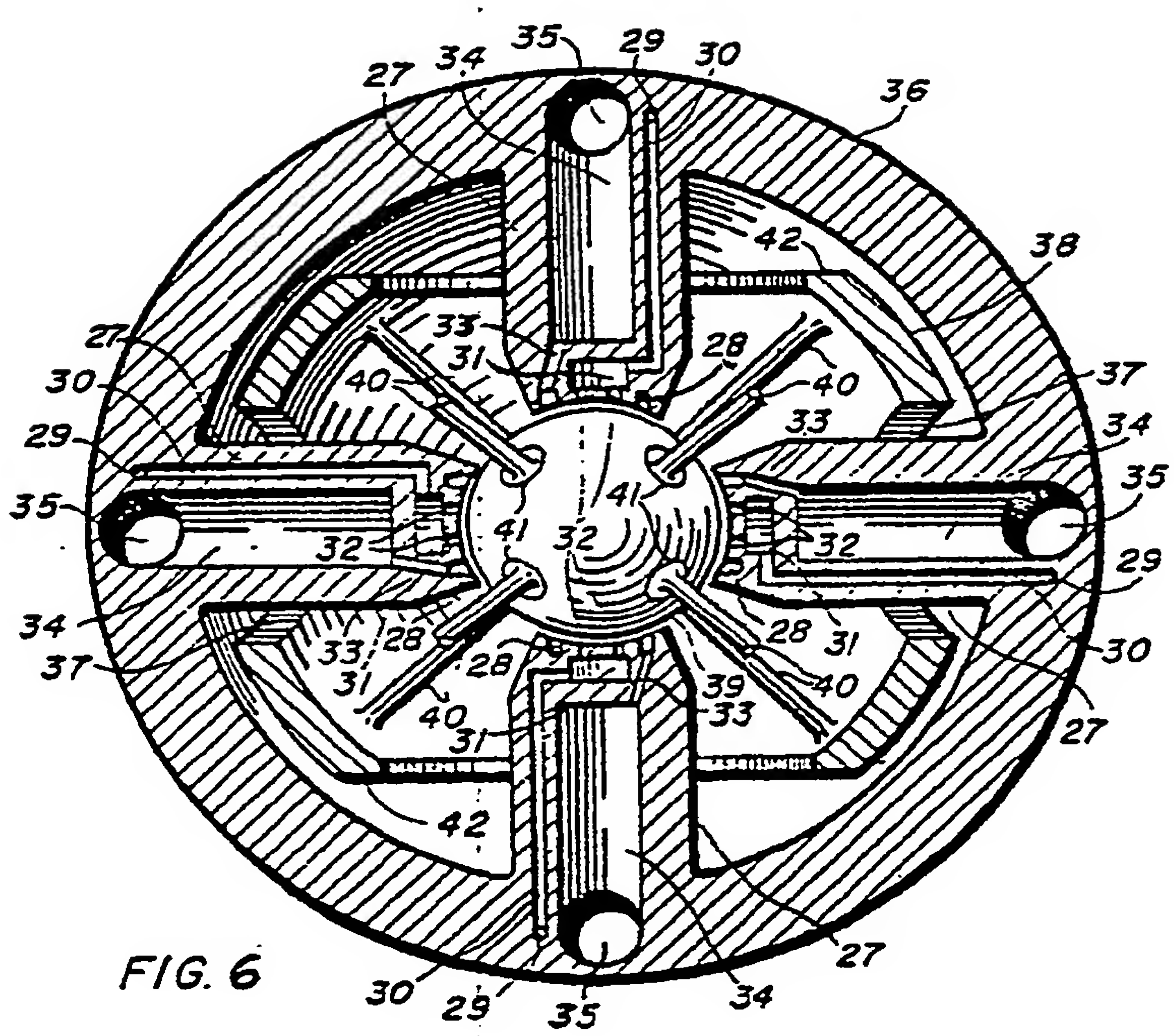

FIG. 6

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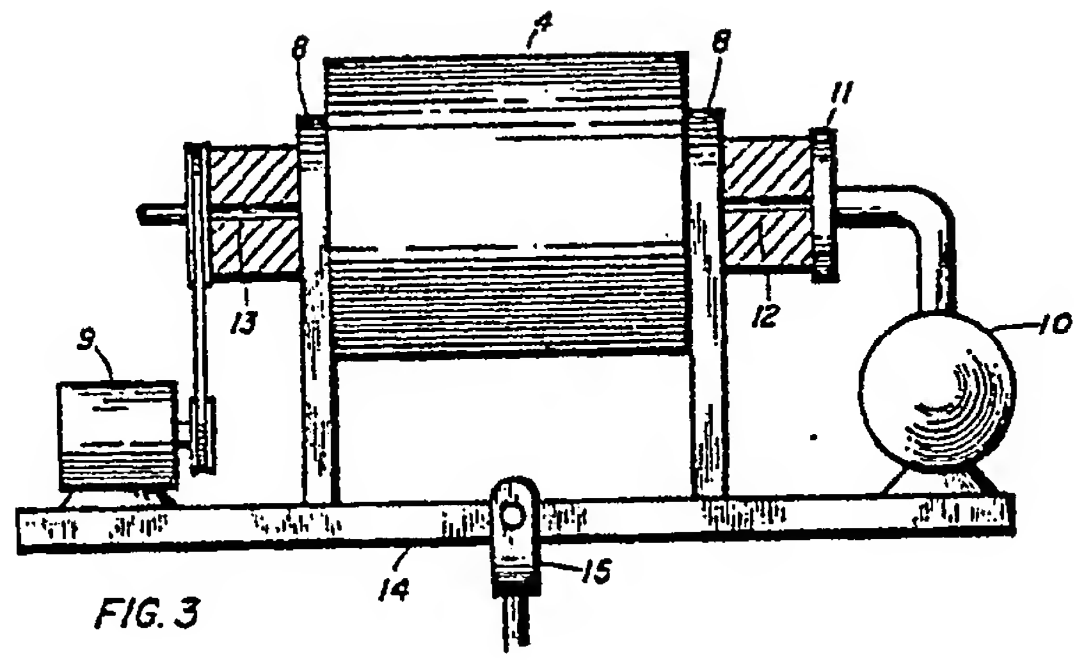

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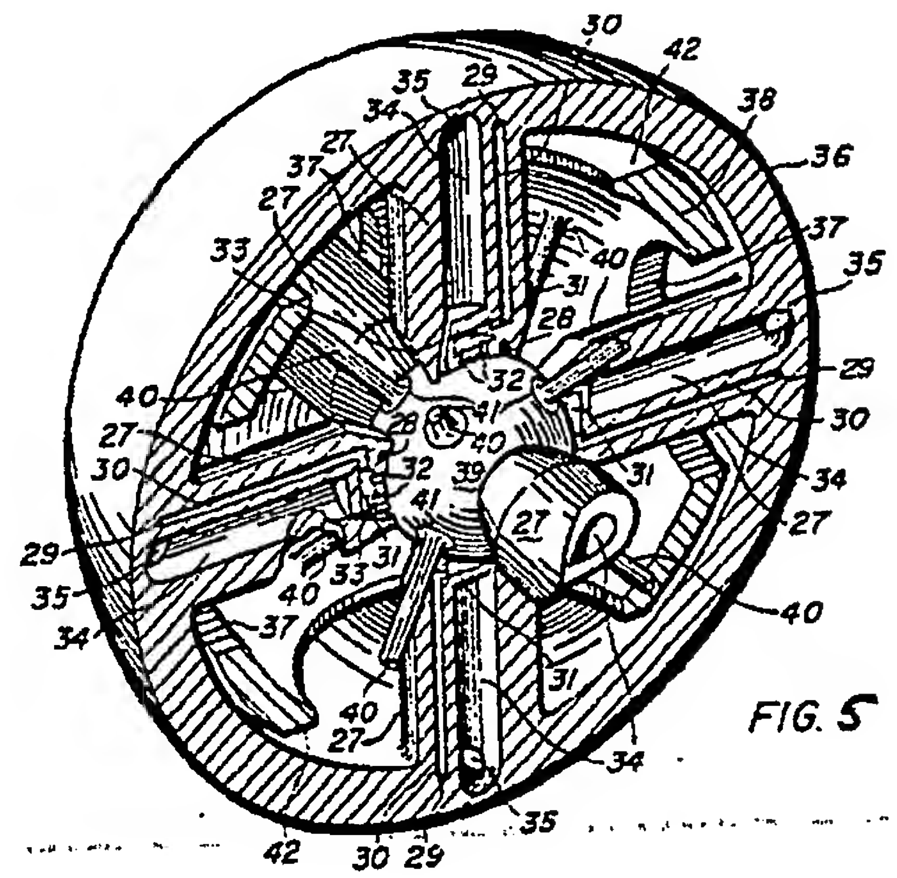

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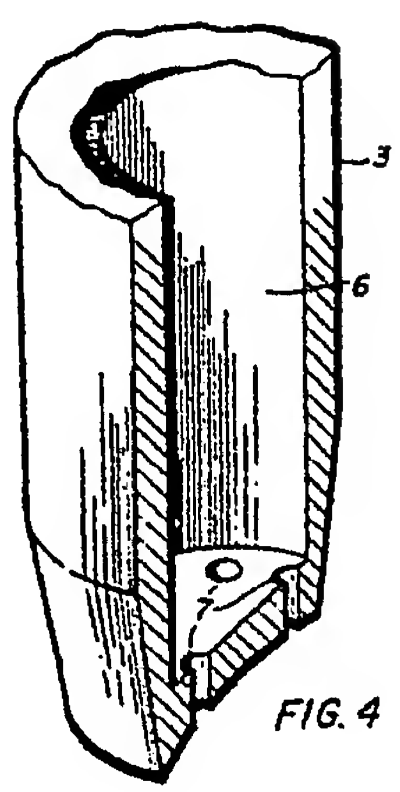

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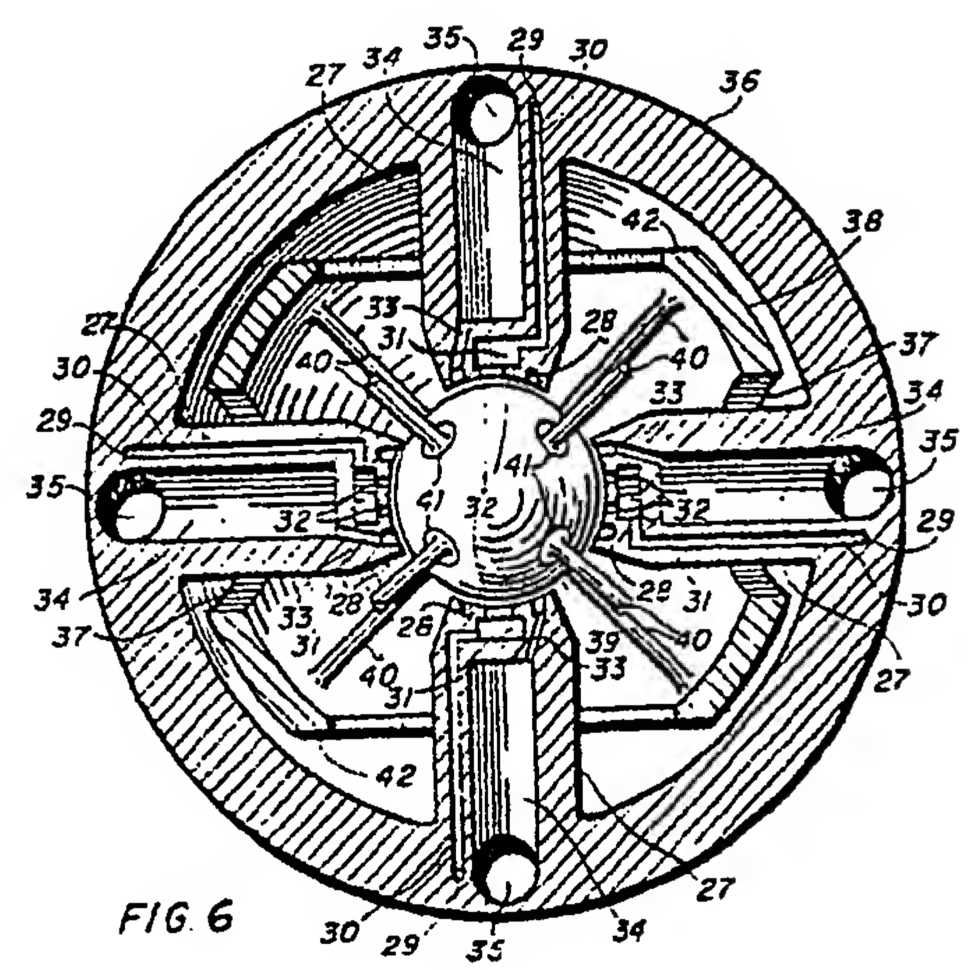

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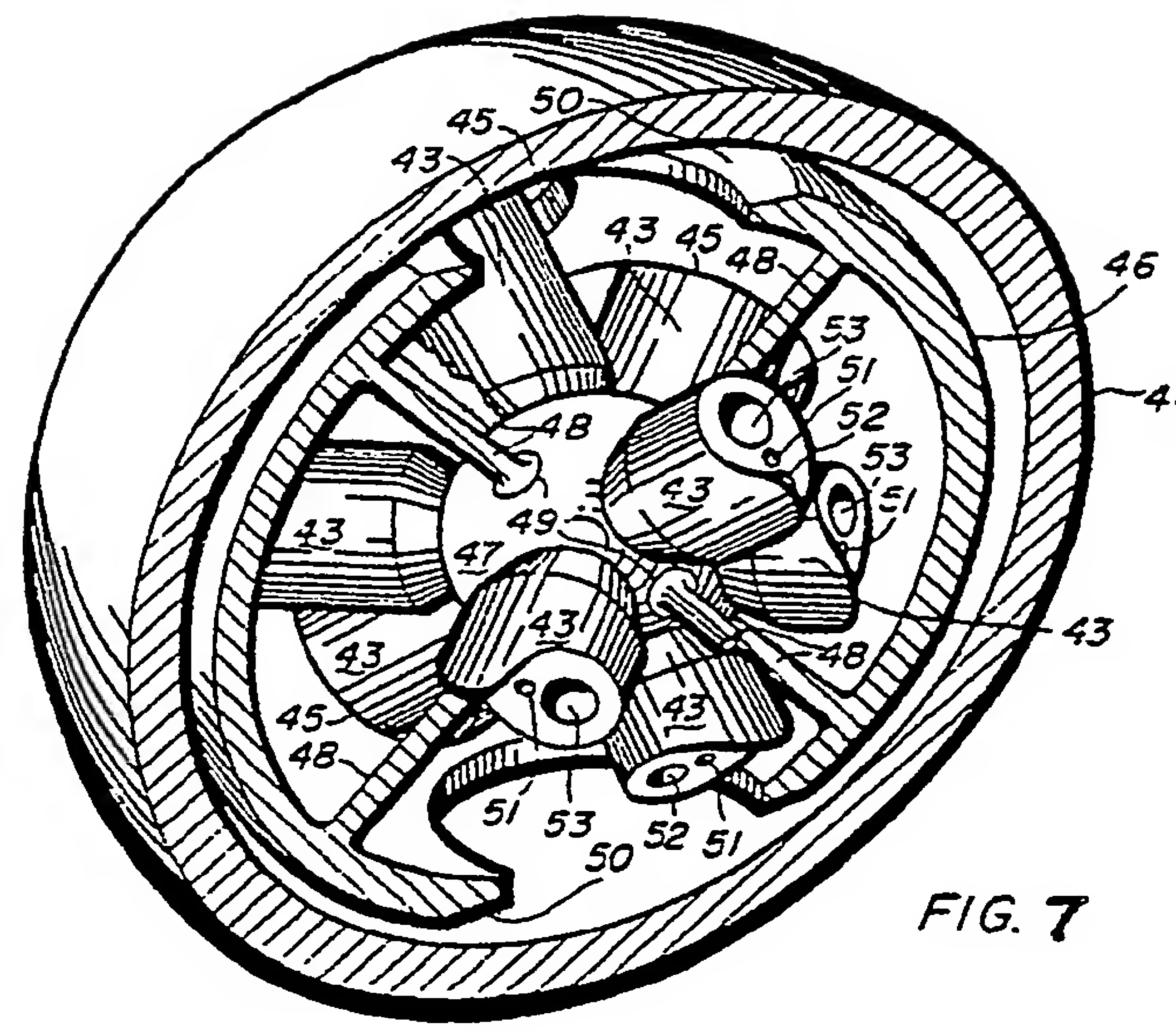

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FIG. 7

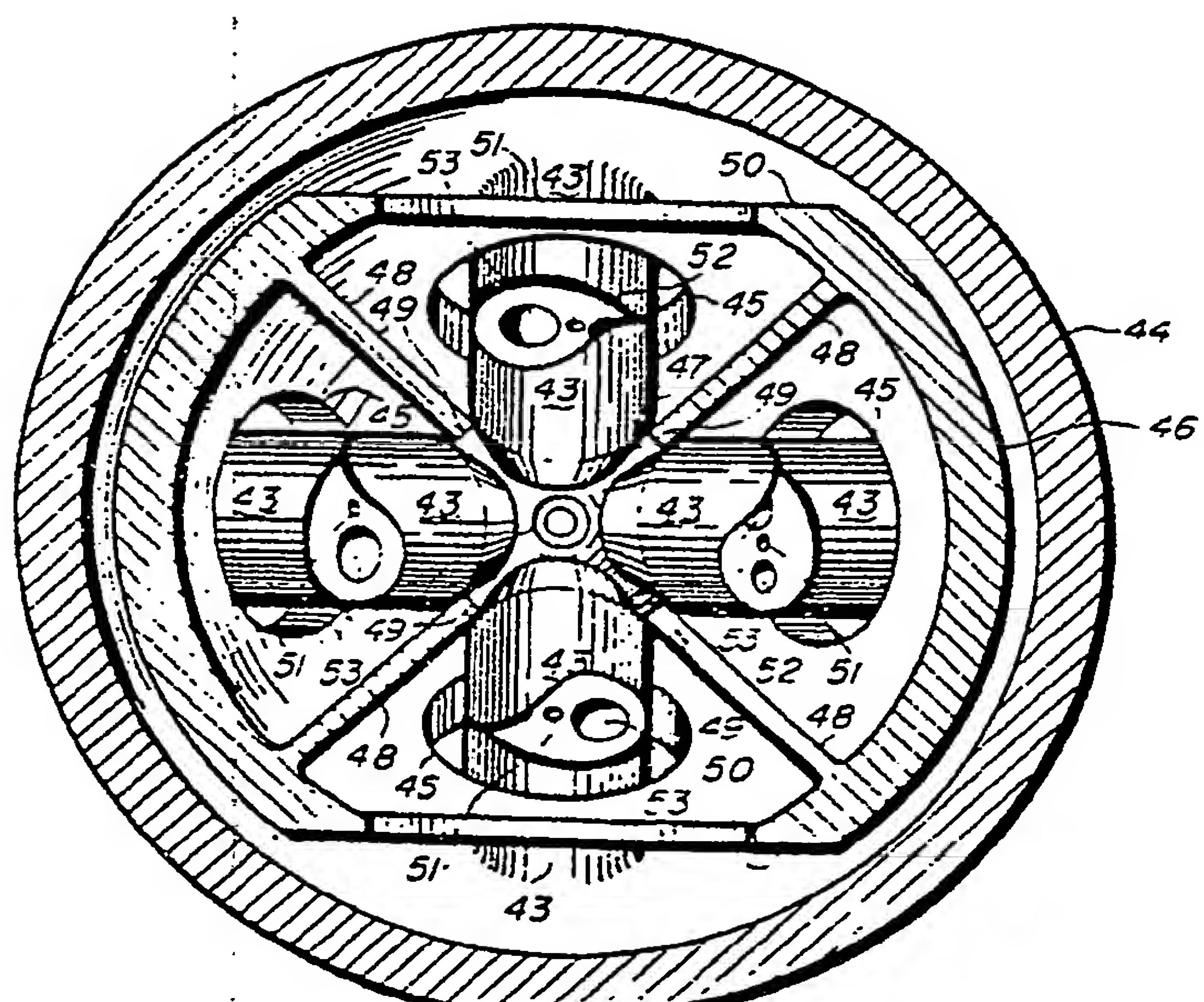

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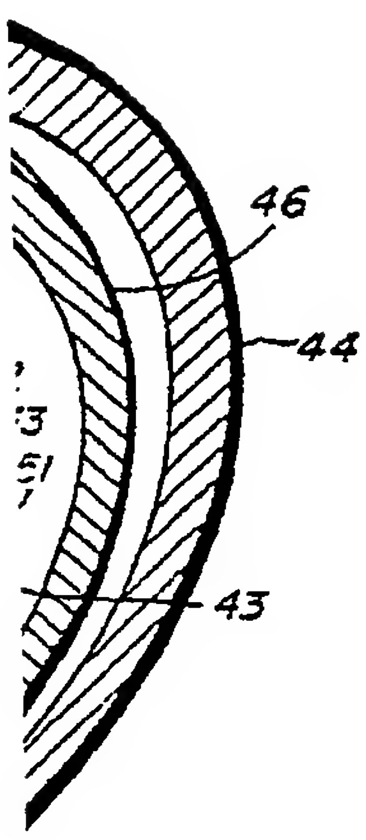
FIG 8



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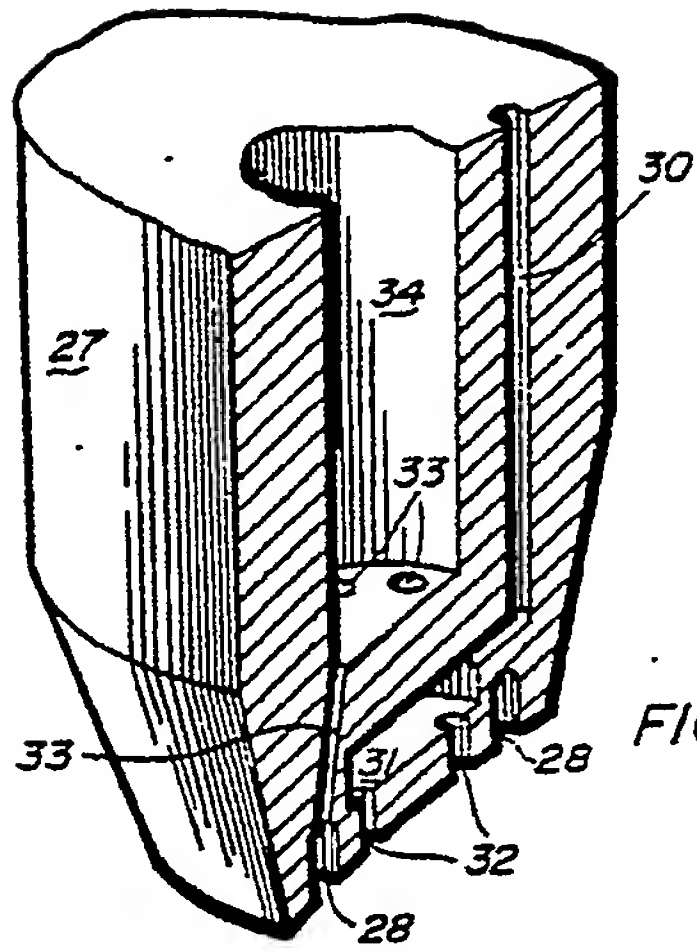

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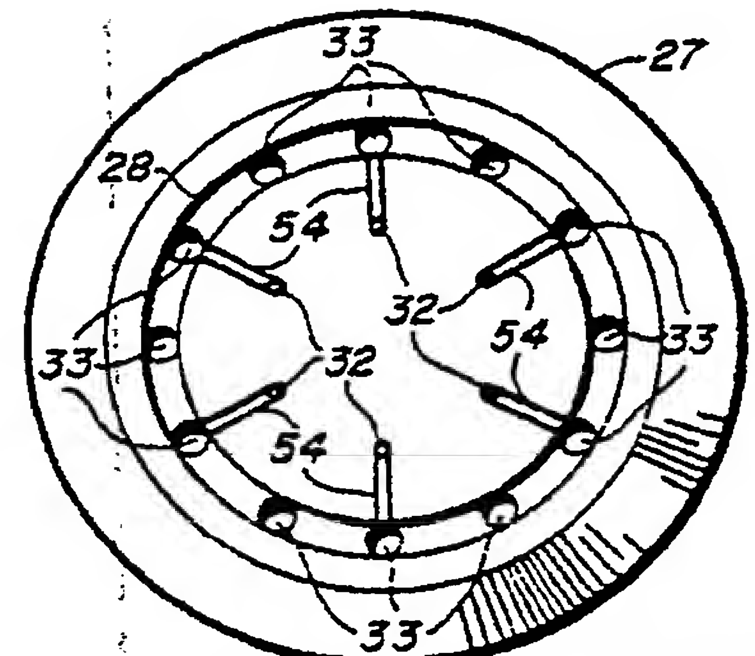
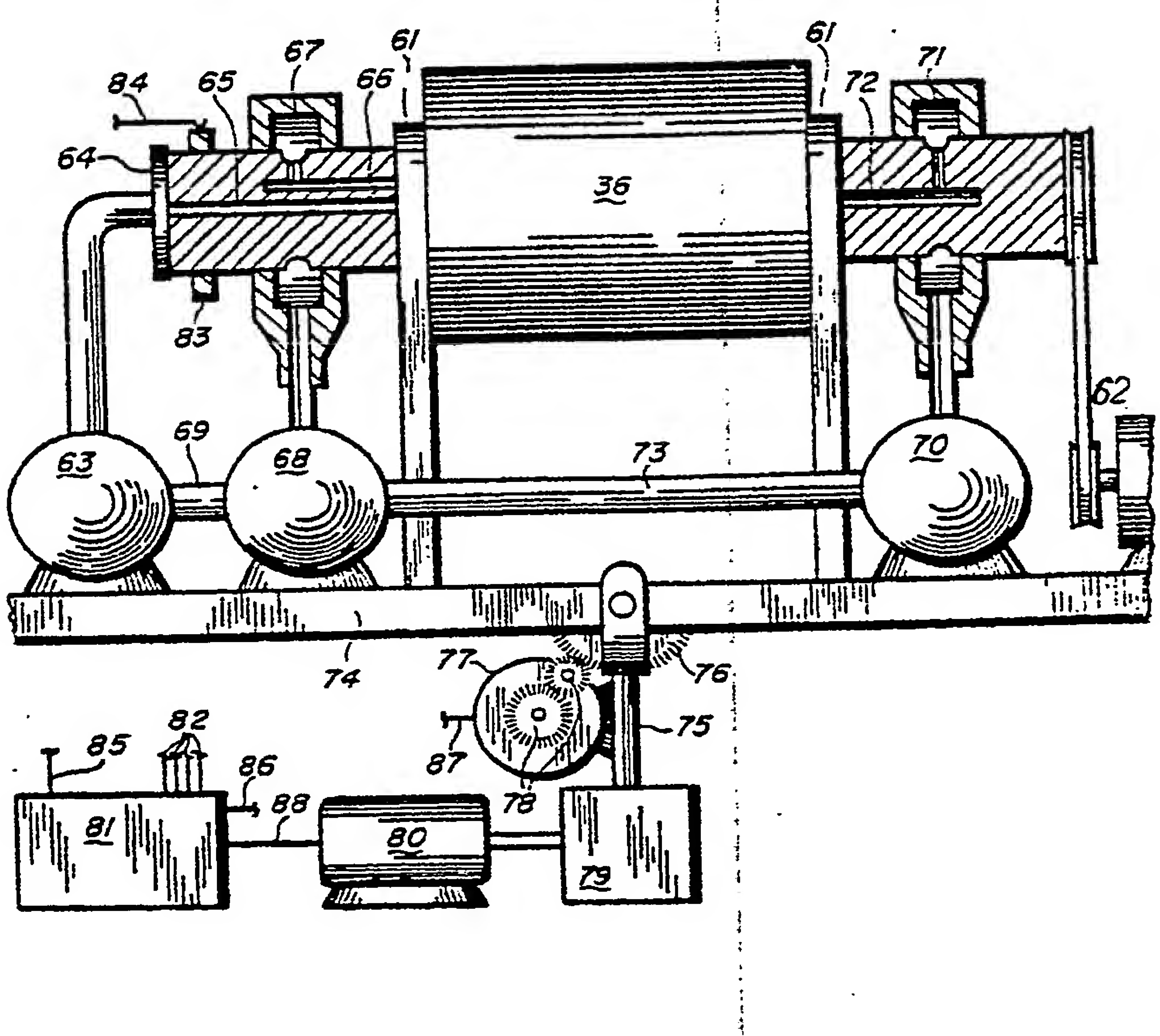


FIG. 10

FIG. 11



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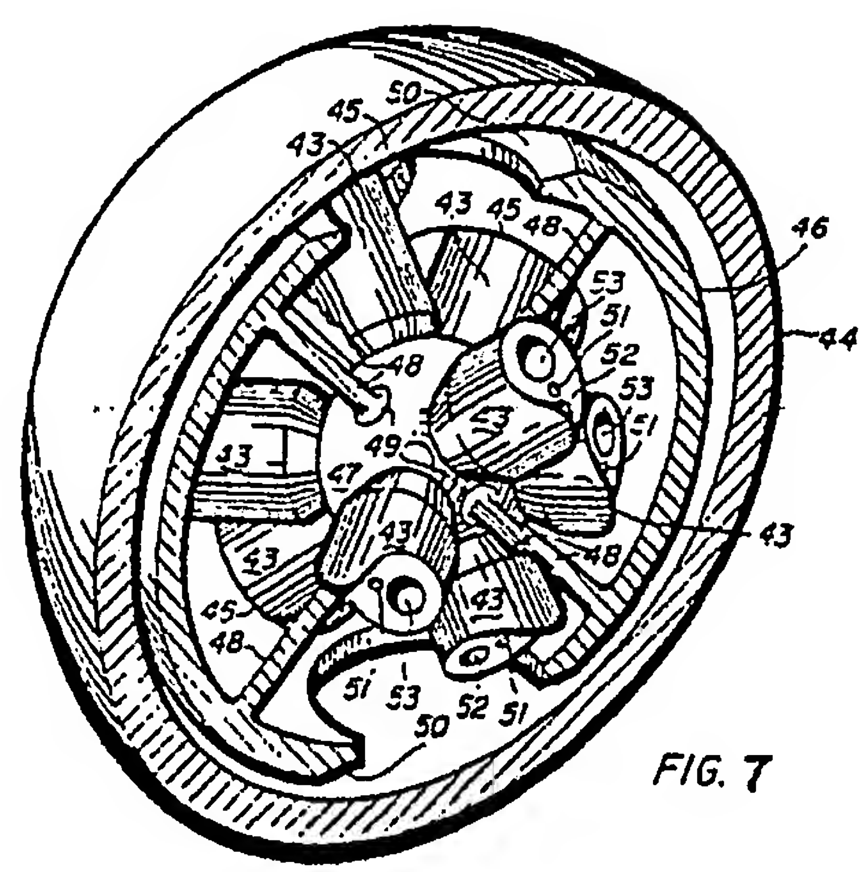

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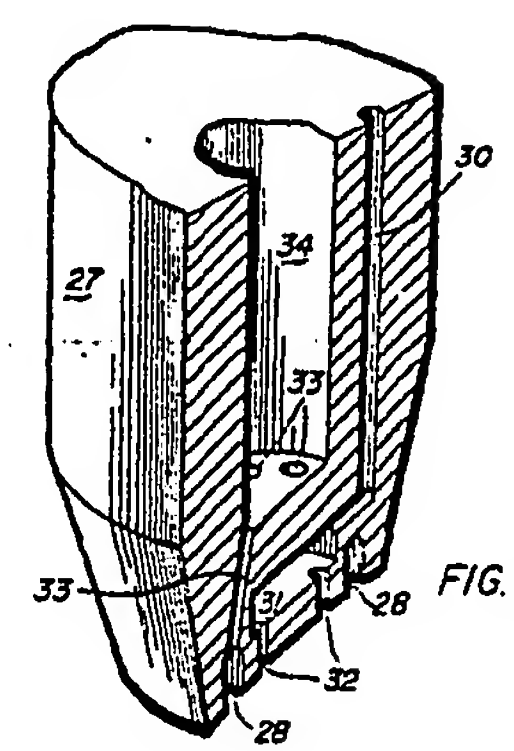

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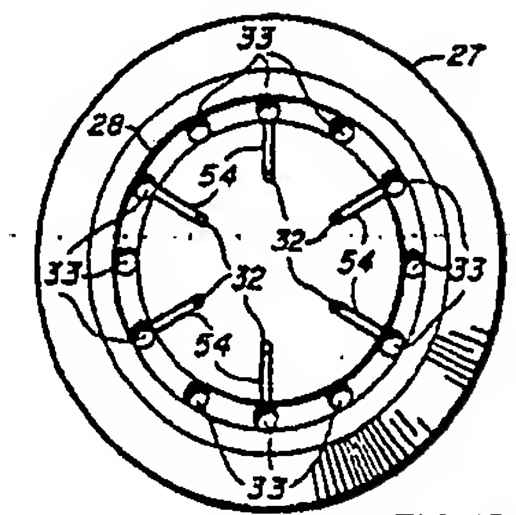

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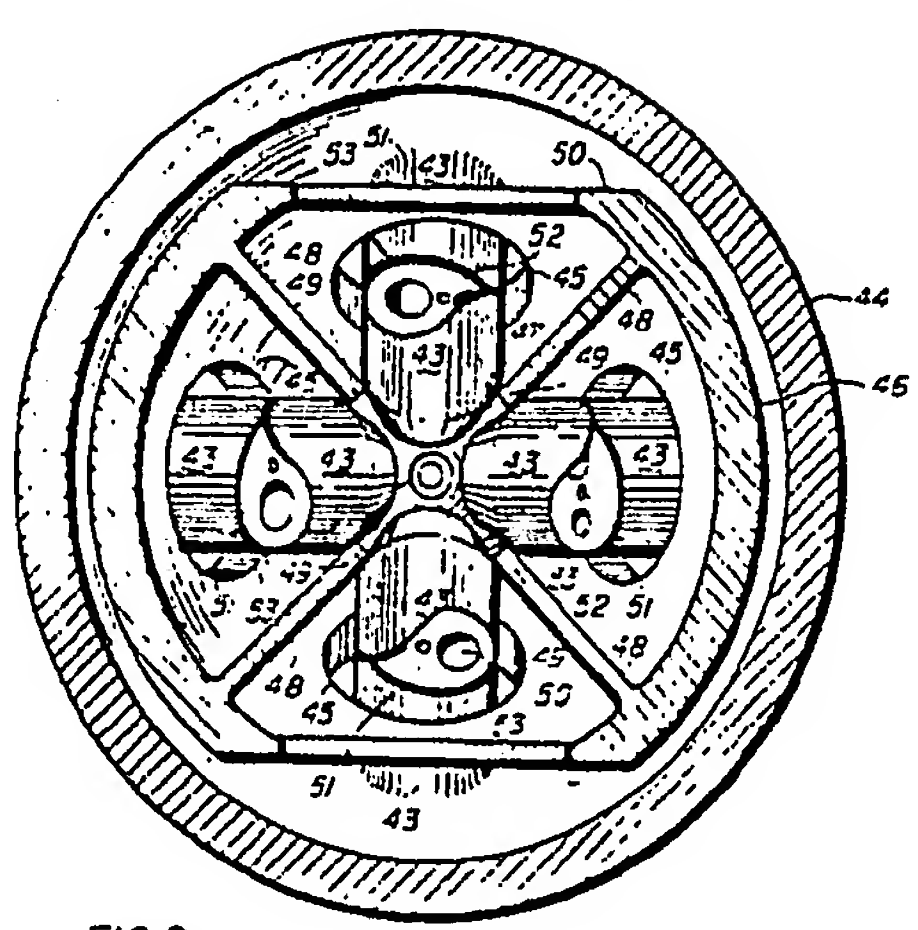
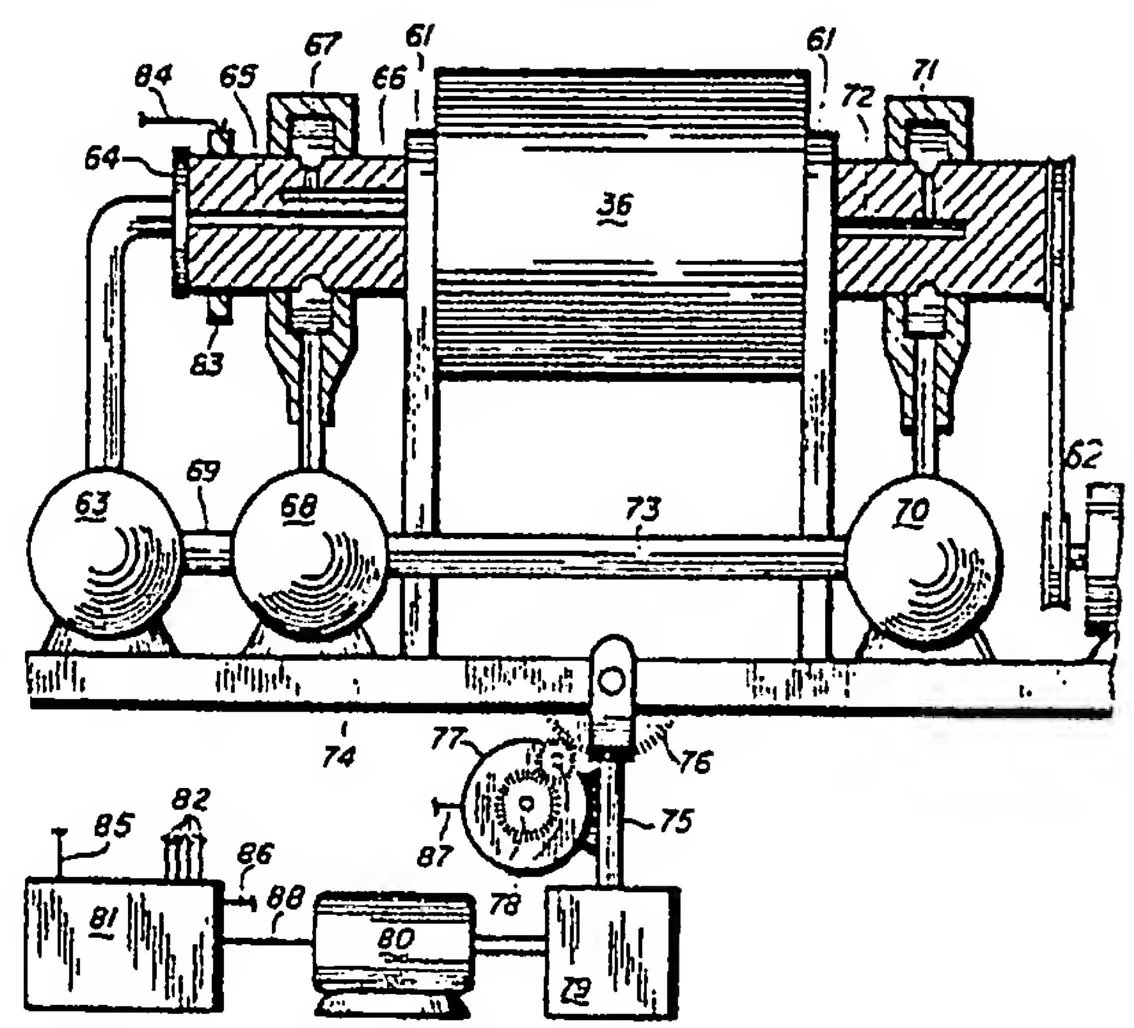


FIG 8

FIG. 11



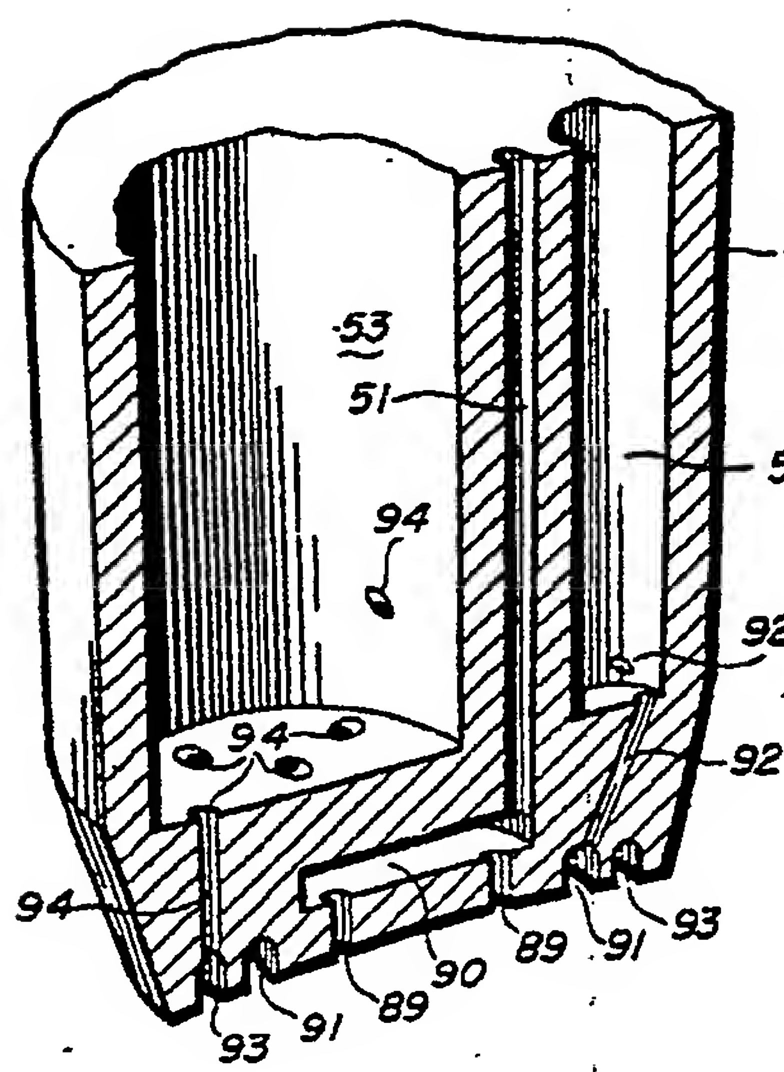

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FIG. 12

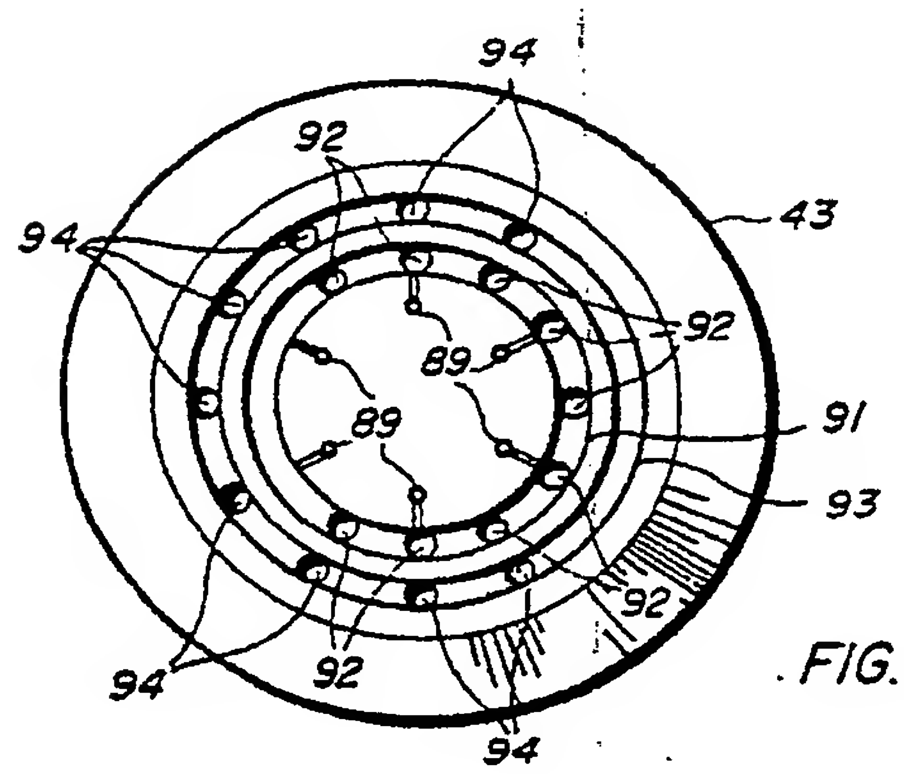
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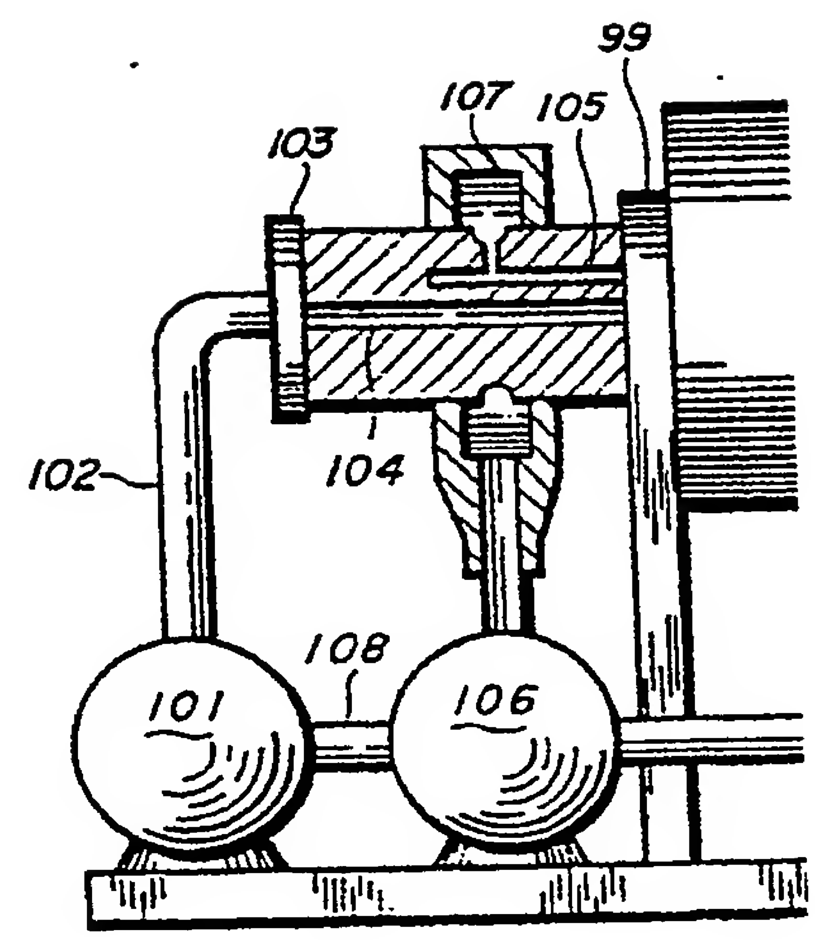
FIG. 13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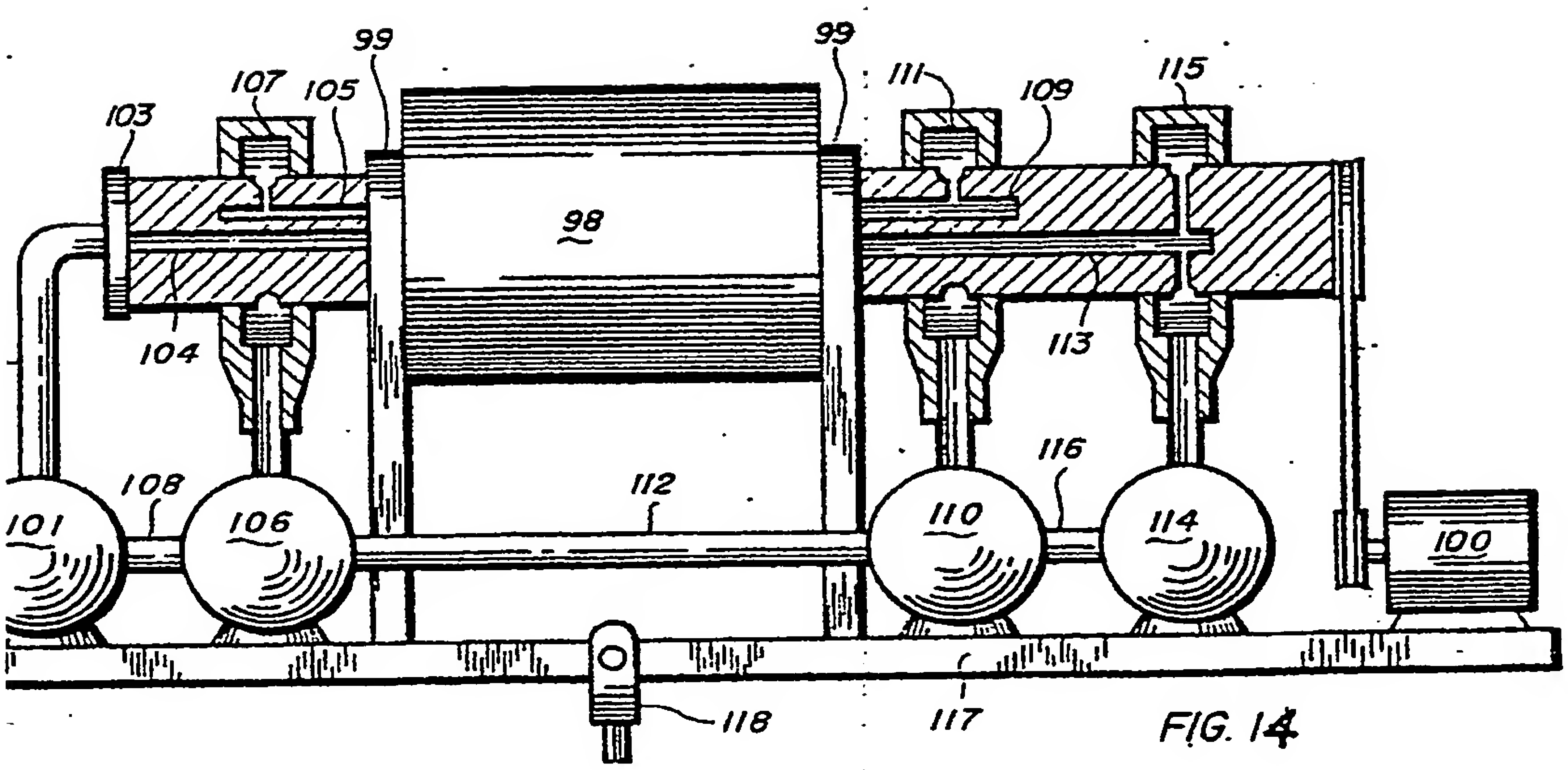

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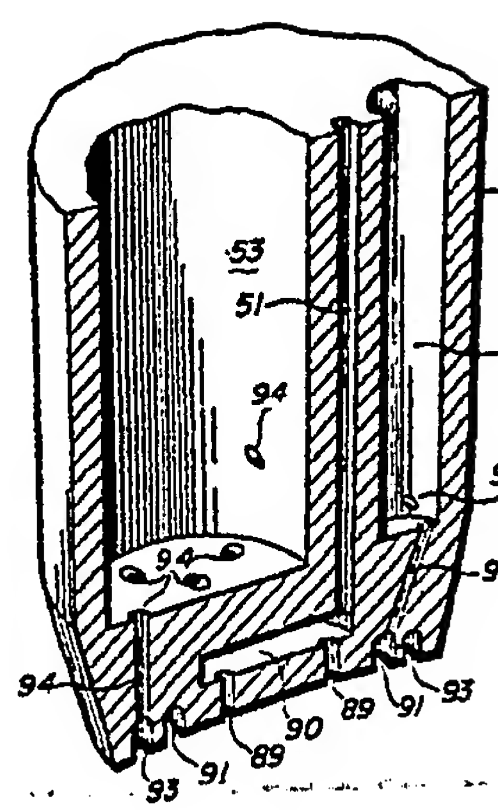

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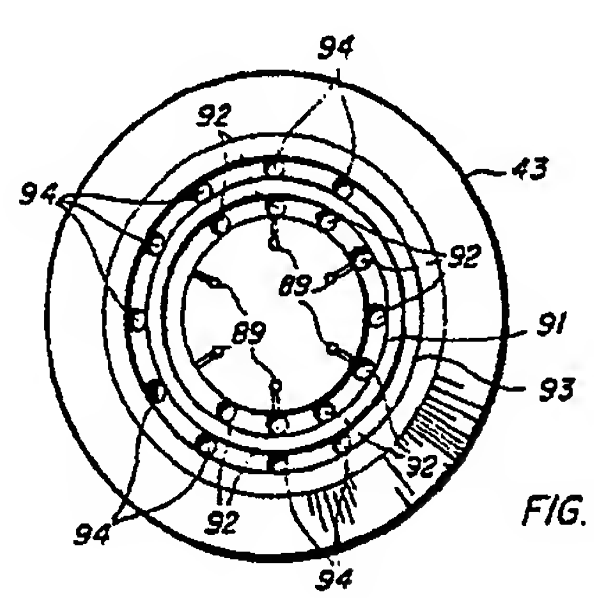

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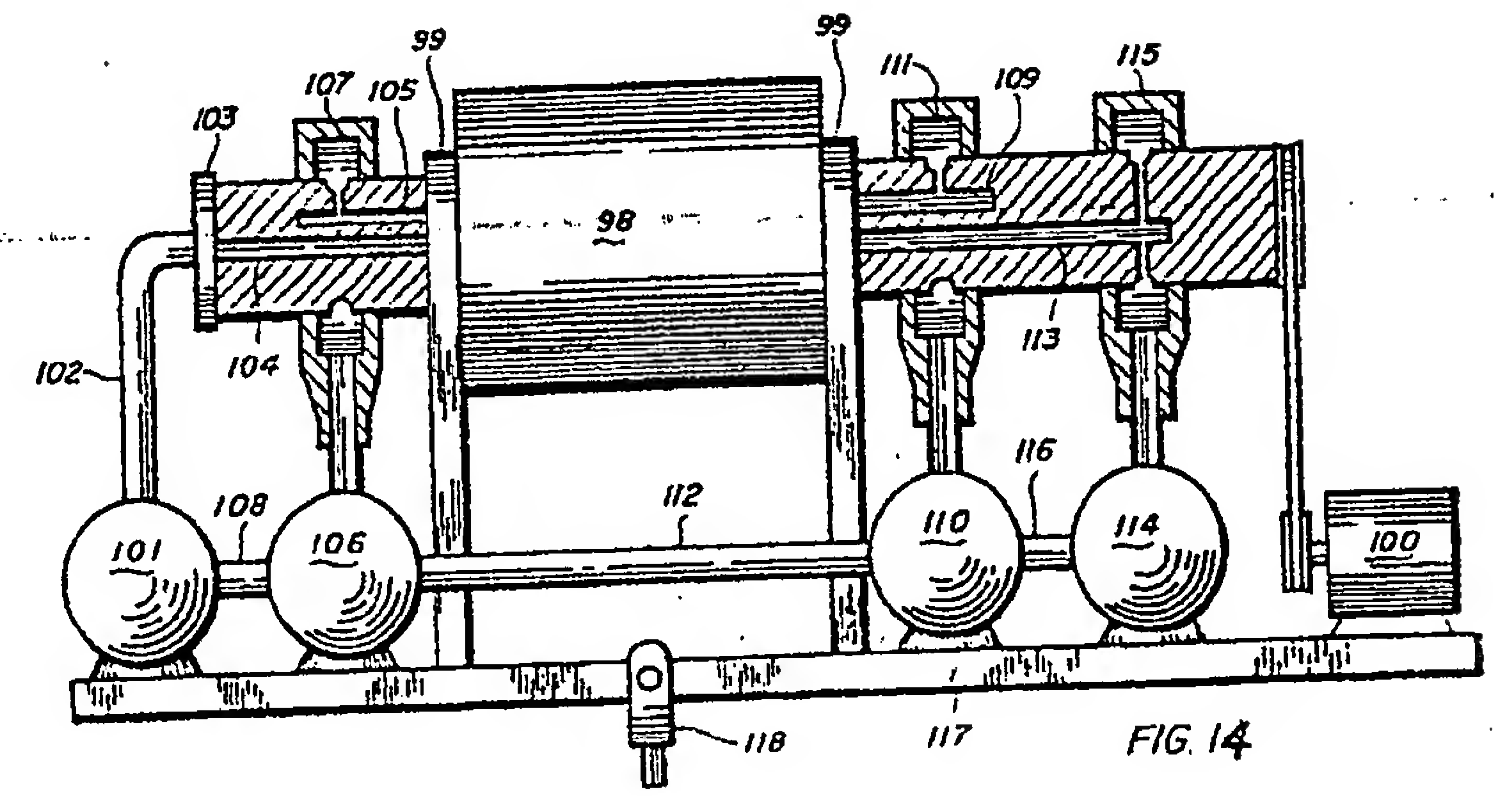

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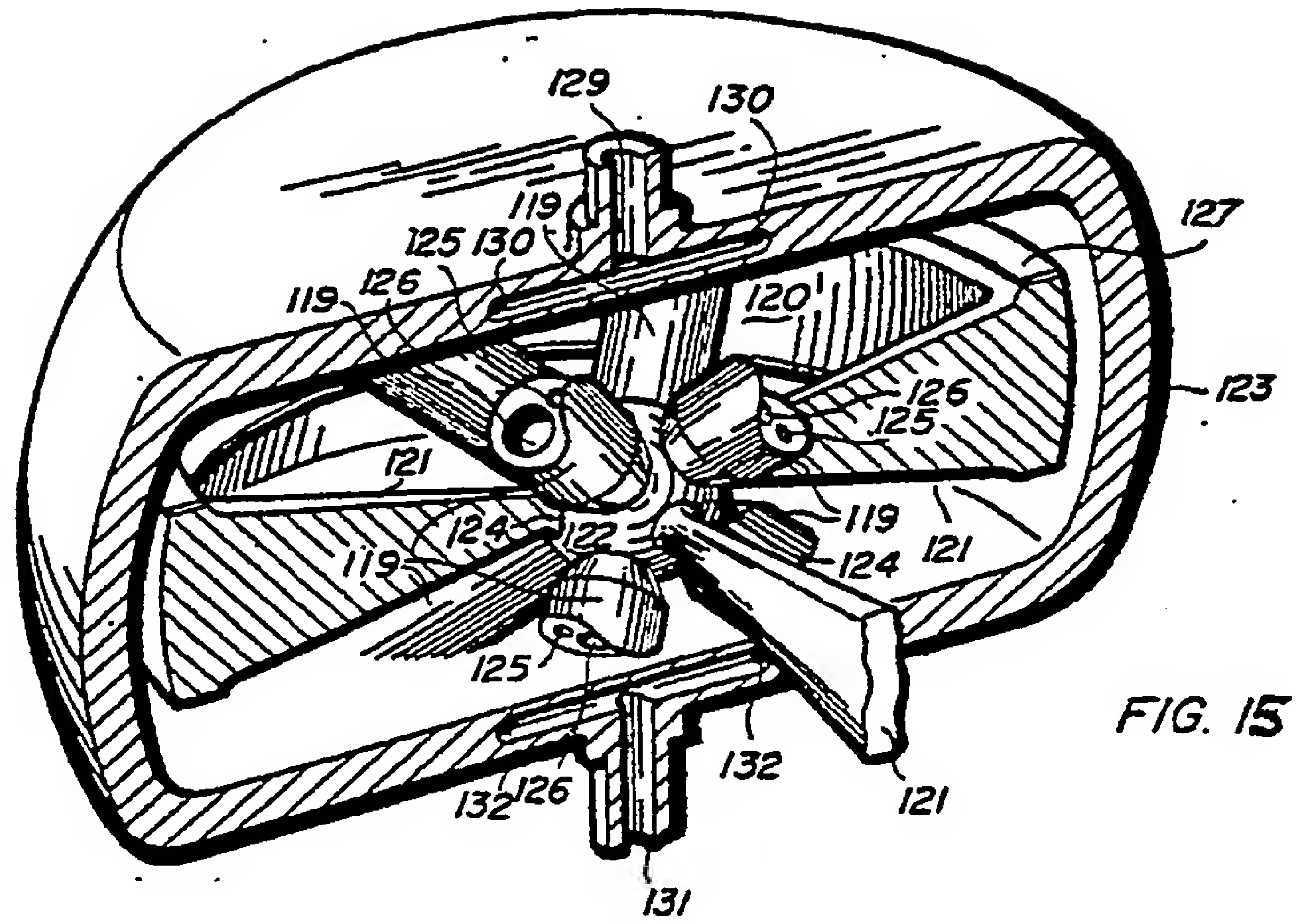
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FIG. 15

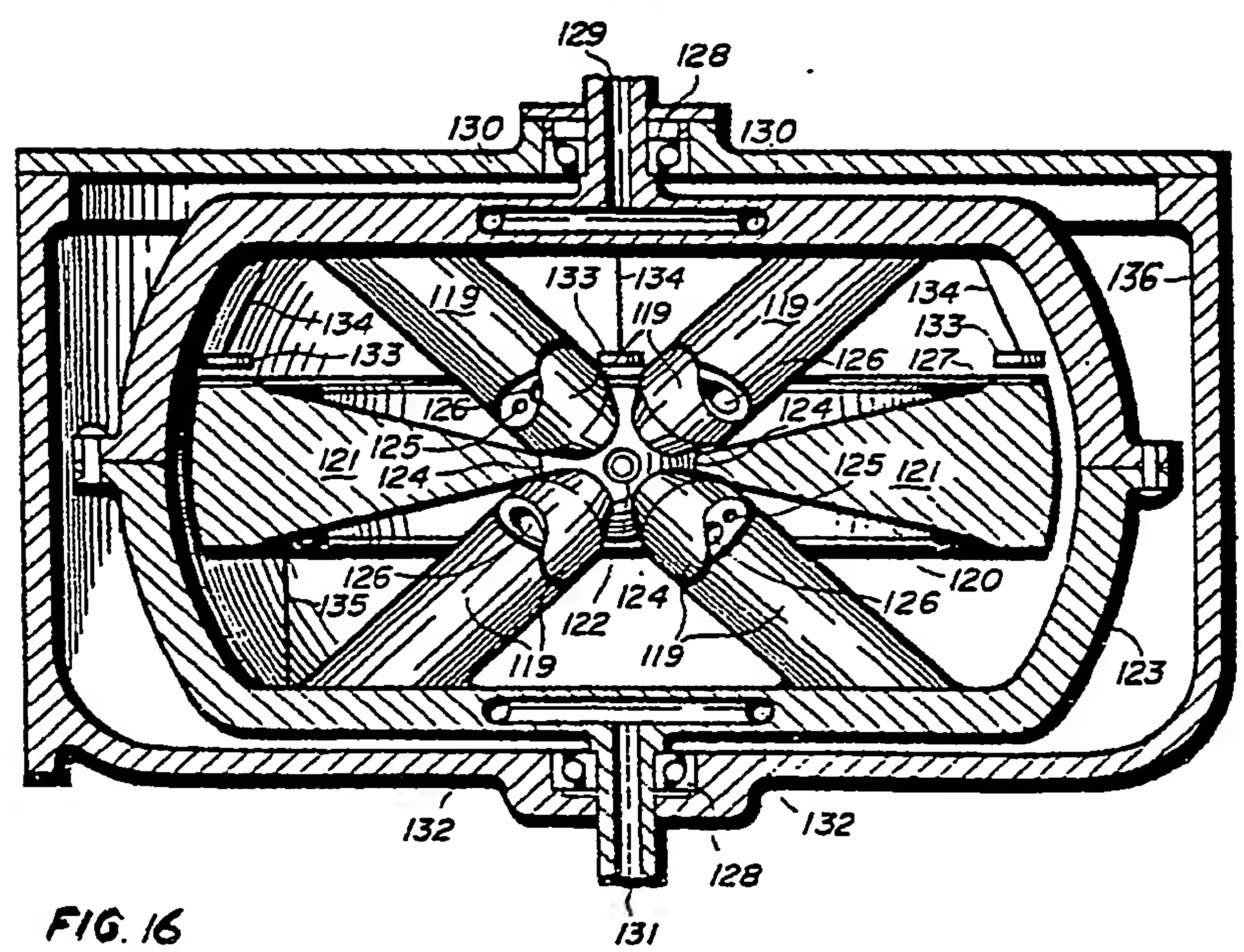
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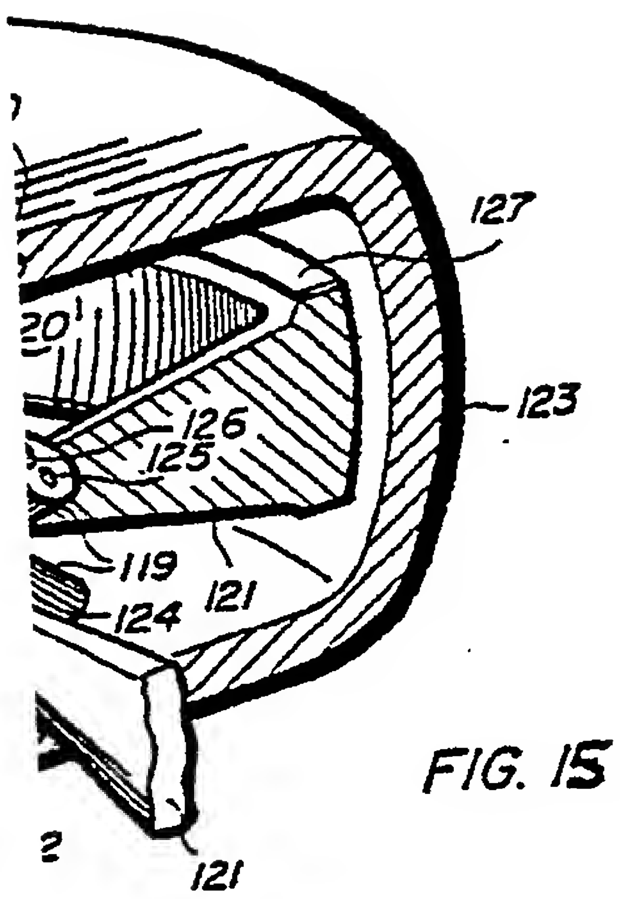
FIG. 16



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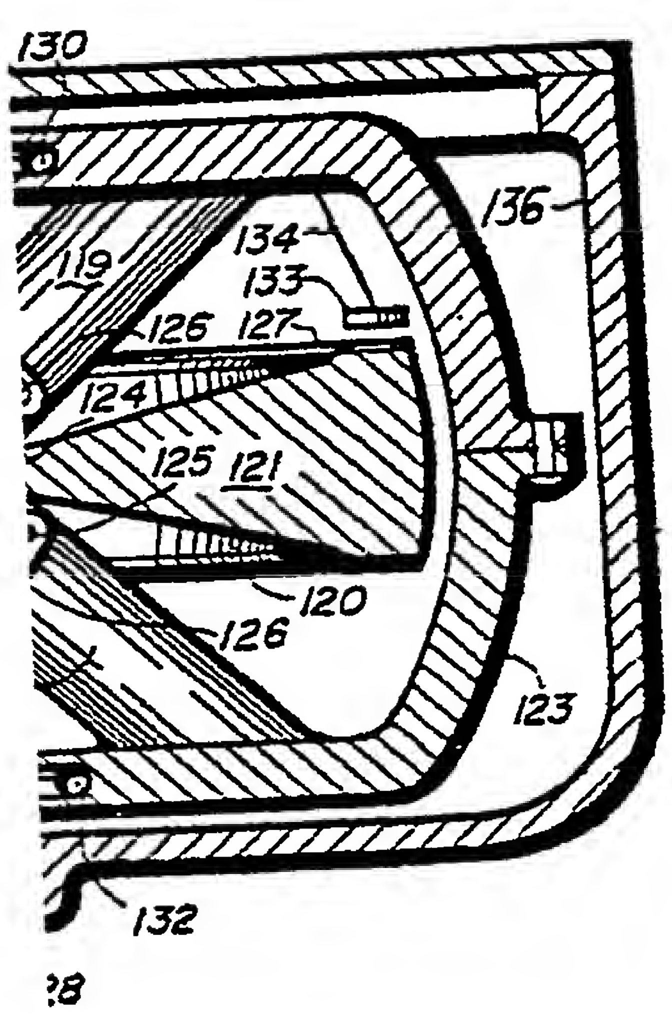

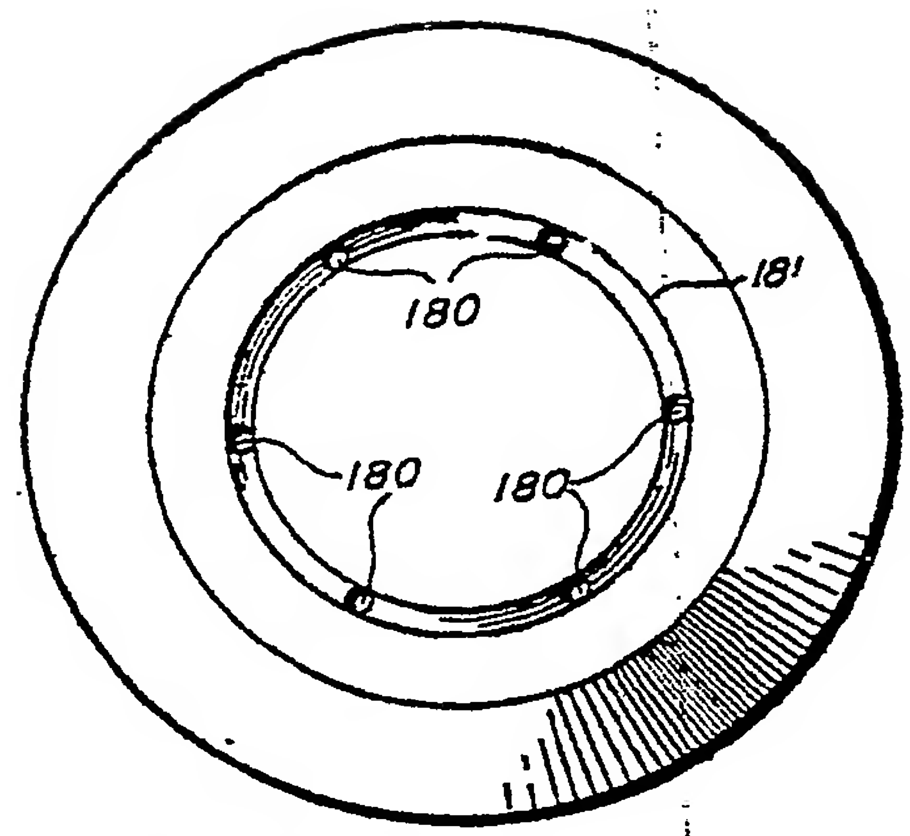

FIG. 17

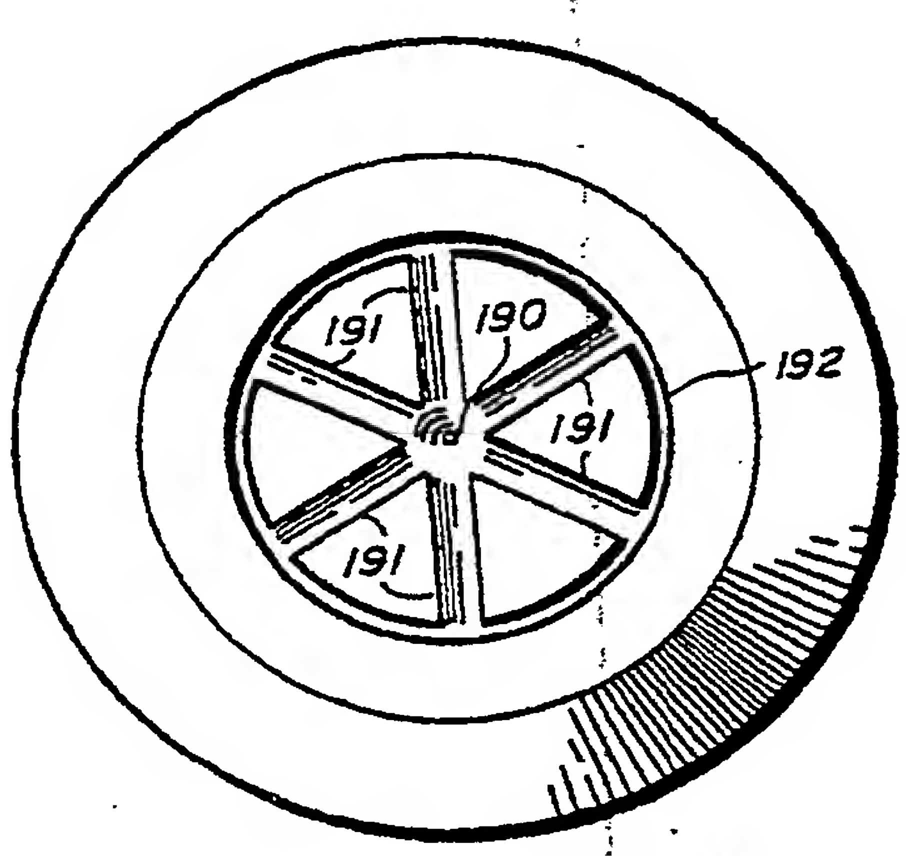

FIG. 18

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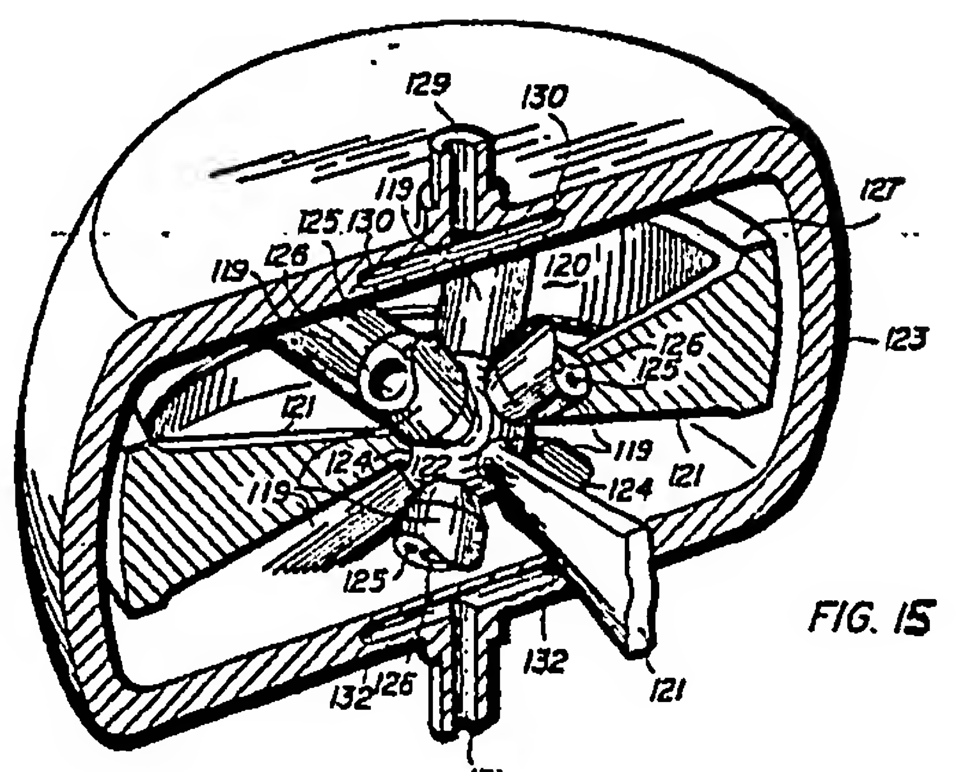

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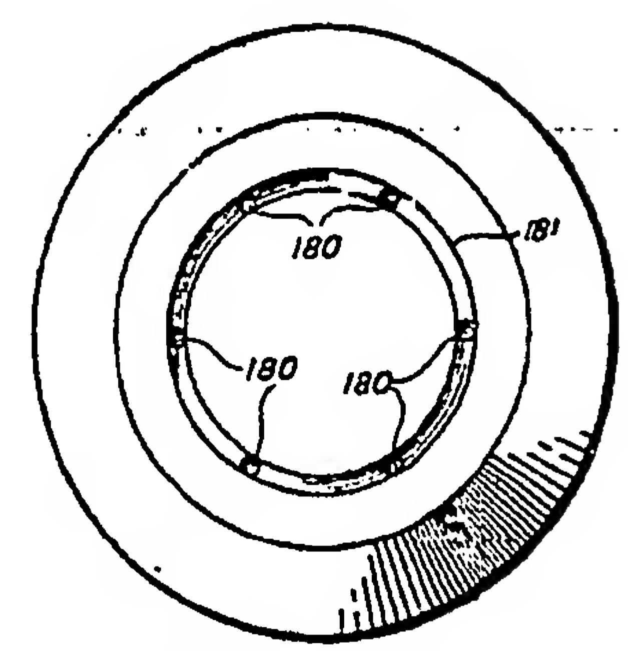

FIG. 17

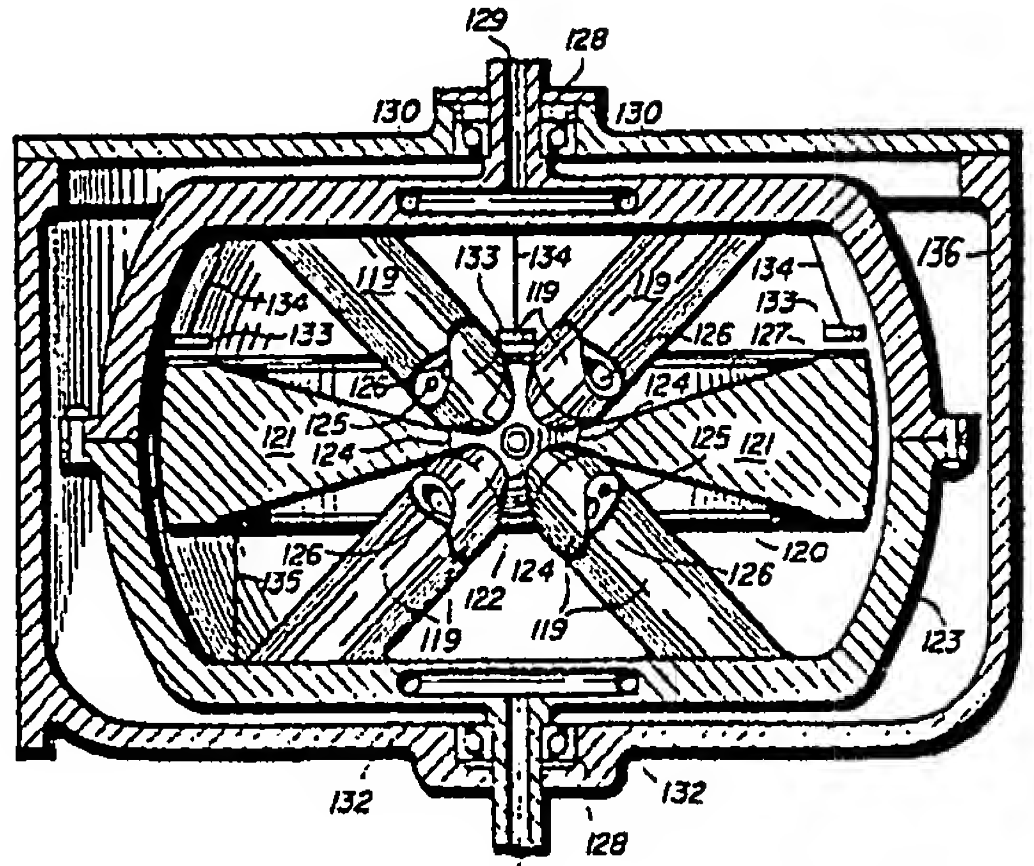

FIG. 16

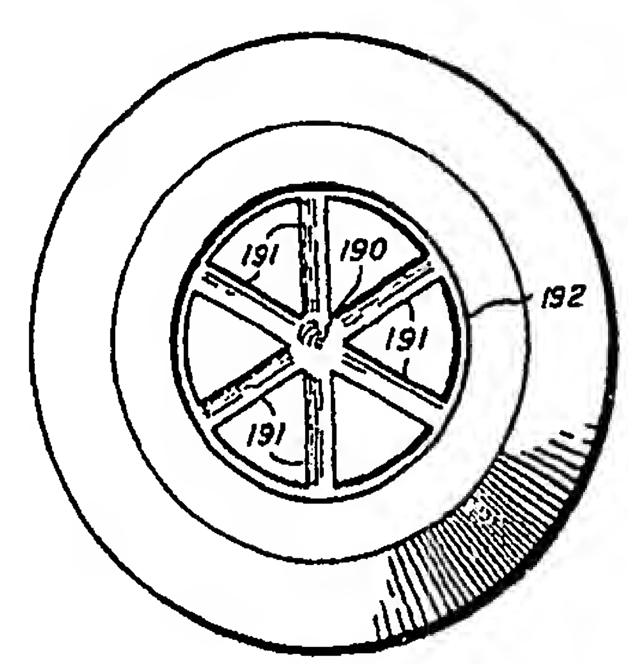

FIG. 18